RHIC
A Physics Facility for the New Millennium

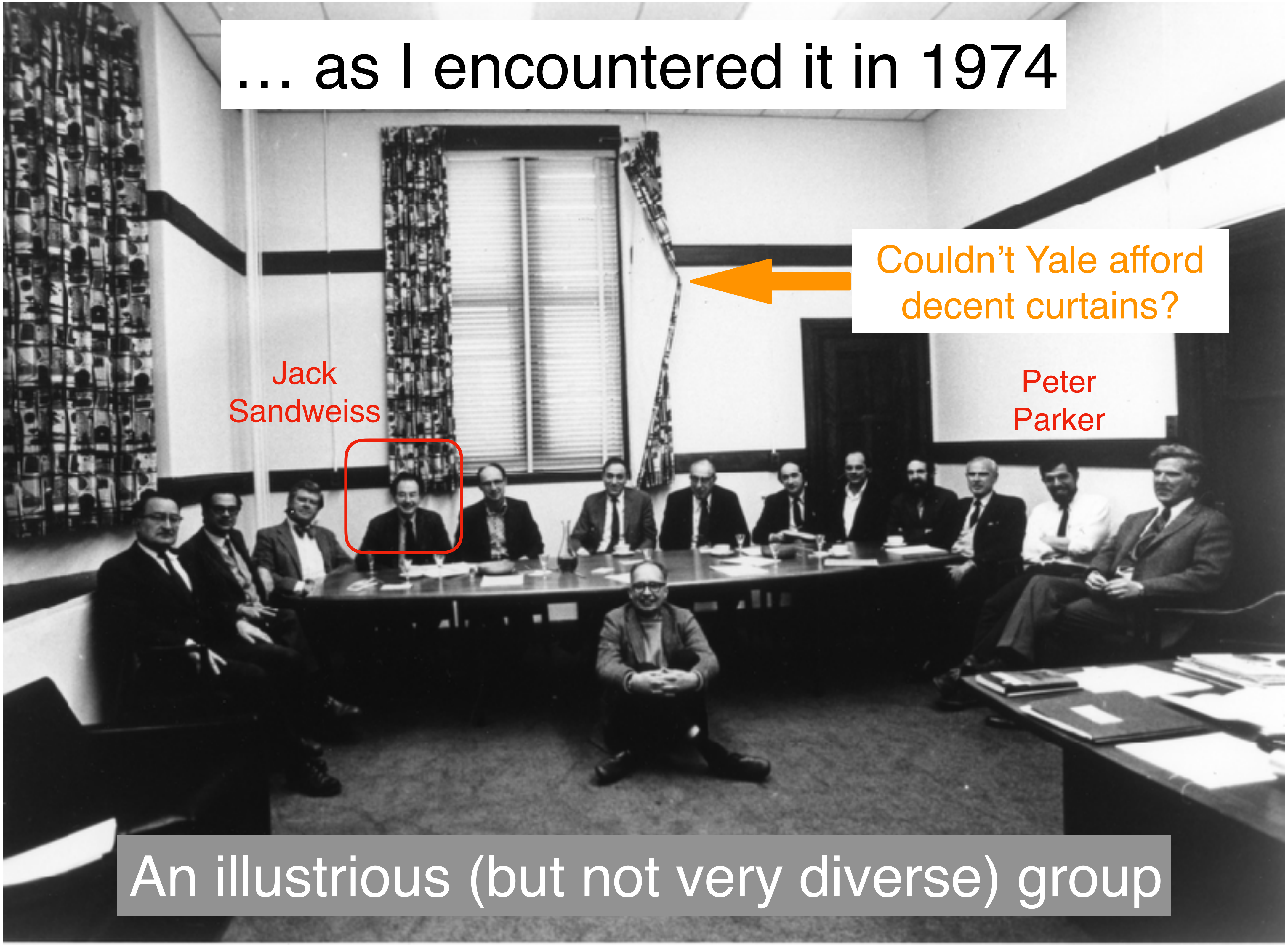
Berndt Müller

Jack Sandweiss Memorial Lecture

Yale University

13 May 2022

Yale tenured Physics faculty…



Jack Sandweiss (1930-2020)

Mel Schwartz, Jack Sandweiss, Tini Veltman, and Jack Steinberger conversing
(*Photo: Emilio Segre Archives, APS*)

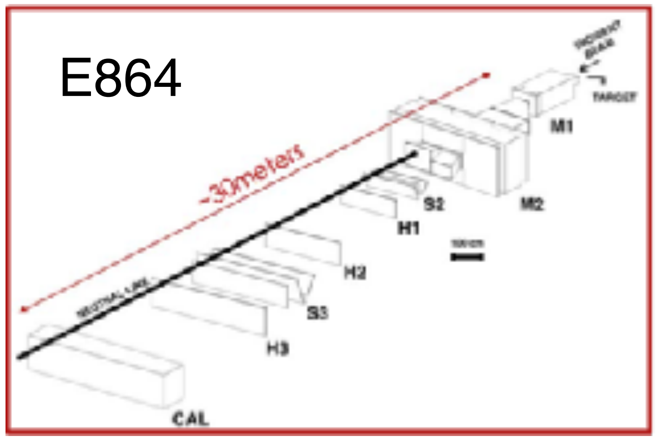
Jack in the company of Nobelists:
Melvin Schwartz (1988)
Jack Steinberger (1988)
Martinus Veltman (1999)

The (unspoken) motto:

An experiment isn't really worth doing if its result could not be worth a Nobel Prize.

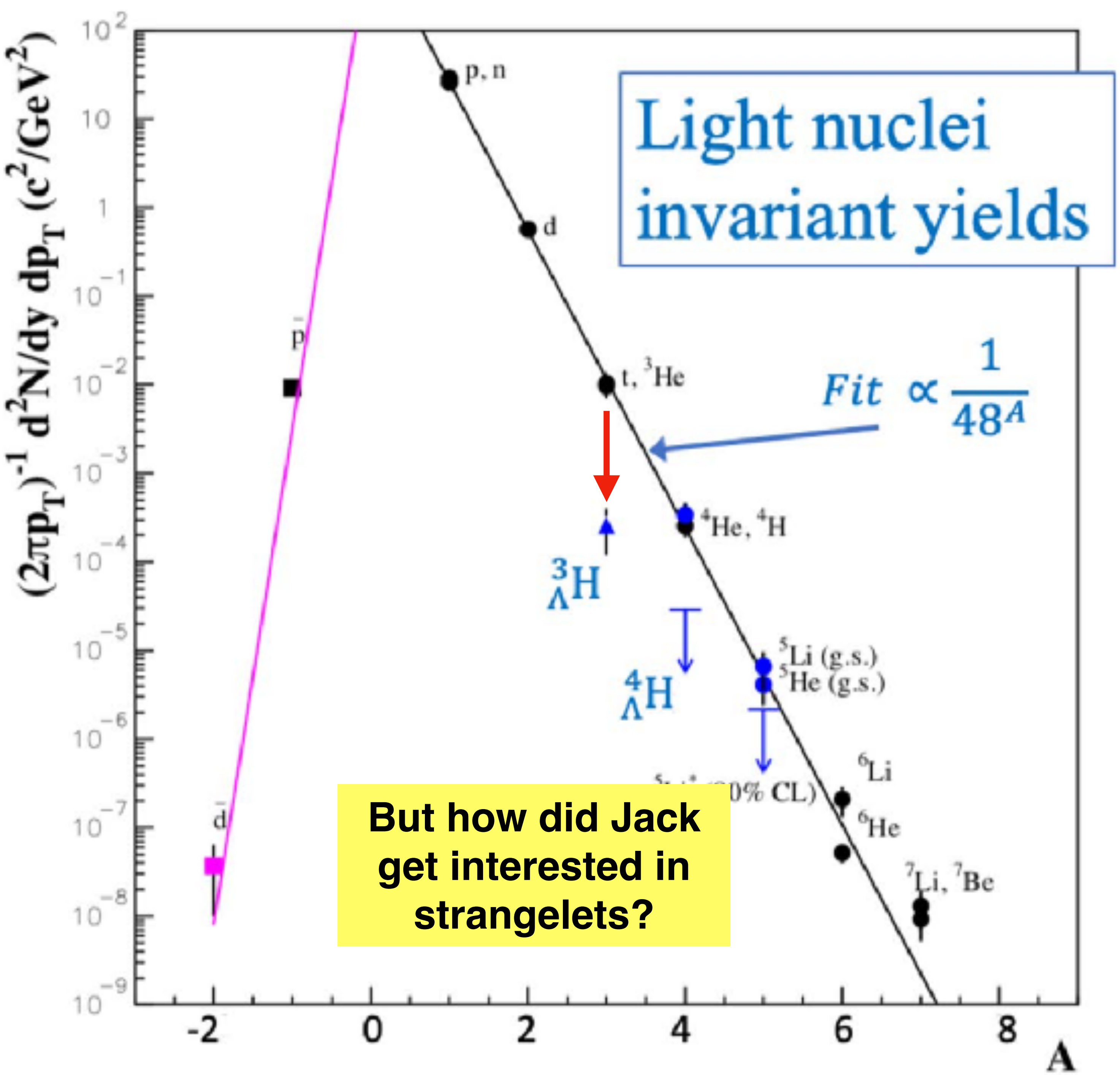
Note that it does not guarantee a result worthy of a Nobel Prize, because you can't control the outcome of the experiment.

Jack's first heavy ion physics experiment (AGS E864) proves the point.



The declared purpose of E864 was to search for charged or neutral, stable or metastable ($\tau > 50$ ns) *strangelets, i*.e. atomic nuclei with strangeness $|S| \gg 1$. It did not find any, but it produced a host of interesting results on the production of small nuclei in heavy ion collisions.

Lessons from E864



You can produce complex nuclei by colliding heavy ions, but there is a "penalty factor" for each additional nucleon. States with large *A* are exponentially suppressed:

$$48^{-A} = e^{-A(m_N - \mu_B)/T}$$

For antinuclei:

$$(3 \times 10^5)^{-A} = e^{-A(m_N + \mu_B)/T}$$

$$\rightarrow \quad T = 112 \text{ MeV} \qquad \mu_B = 493 \text{ MeV}$$

States with |S| > 0 incur an additional penalty factor ~ 0.36 ± 0.26.

Conclusion:

You can't produce strangelets (if they exist) with measurable yields in heavy ion collisions.

Strangeness as a probe

Experiments with 25-GeV hyperon beam at Brookhaven

A beam of high-energy hyperons has been operated successfully at the Brookhaven Alternating Gradient Synchrotron. The beam was designed and constructed by a team from Yale University, the National Accelerator Laboratory and Brookhaven under the leadership of Jack Sandweiss and William Willis from Yale and Joseph Lach from NAL. The availability of a beam of hyperons is expected to lead to a substantial advance in the study of their properties.

PHYSICS TODAY / DECEMBER 1971

APS NEWS

April 2013 (Volume 22, Number 4)

Jack Sandweiss Looks Back on 25 Years at PRL

Ed. Note: *As Jack Sandweiss, the Donner Professor of Physics at Yale University, prepared to leave office after a quarter century as the senior editor of Physical Review Letters, he took time to reflect on his experiences in an interview with Michael Lucibella of* APS News.

Q: How has the journal changed in the 25 years you've been there?

A: It's grown a lot, but it hasn't changed in a fundamental sense. If anything, the standards have probably increased slightly. Our acceptance rate used to be something like 40%, and now it's a little under 30%. *PRL* has gotten bigger, but its basic philosophy hasn't changed. The other thing I would say about it is we've somewhat broadened the areas that we call physics. For example, when I started, something called soft matter physics (polymers, foams, gels, that kind of thing) did not have its own separate

VOLUME 58, NUMBER 18 PHYSICAL REVIEW LETTERS 4 MAY 1987

Separation of Strangeness from Antistrangeness in the Phase Transition from Quark to Hadron Matter: Possible Formation of Strange Quark Matter in Heavy-Ion Collisions

Carsten Greiner, Peter Koch, and Horst Stöcker

Institut für Theoretische Physik, Johann Wolfgang Goethe Universität, D-6000 Frankfurt am Main, West Germany

(Received 10 November 1986; revised manuscript received 25 March 1987)

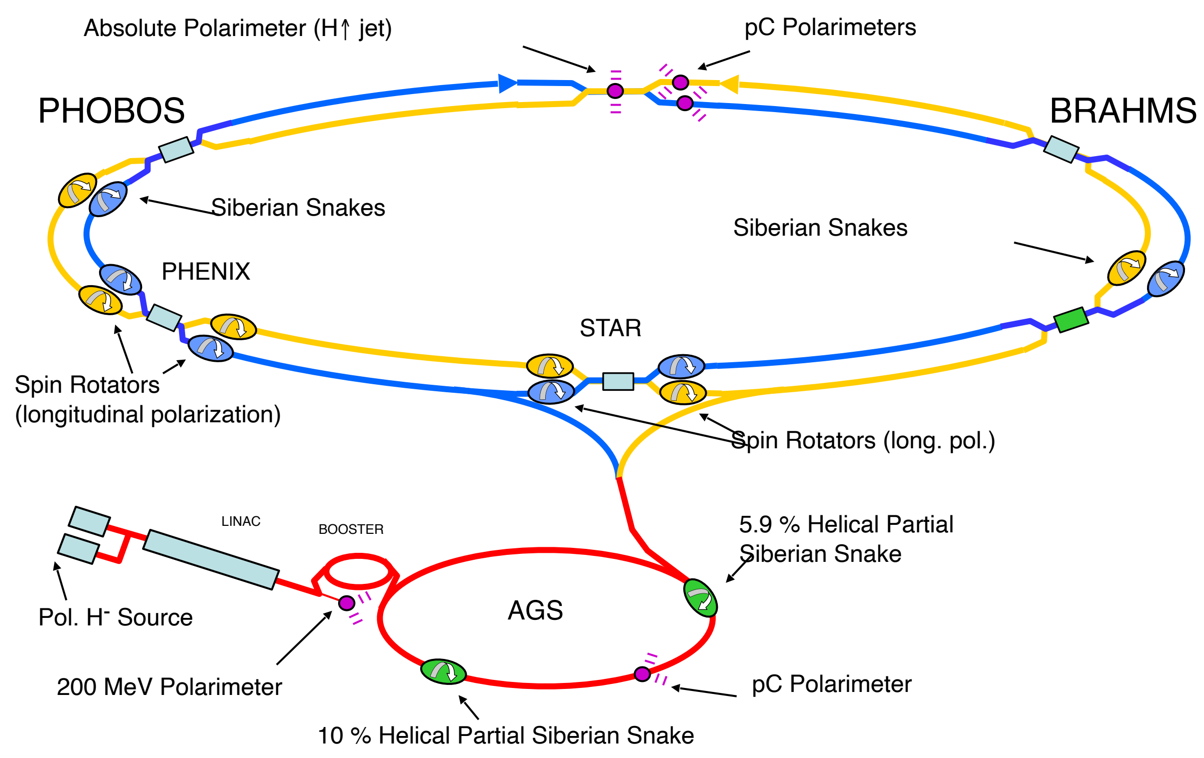
The Path to RHIC I

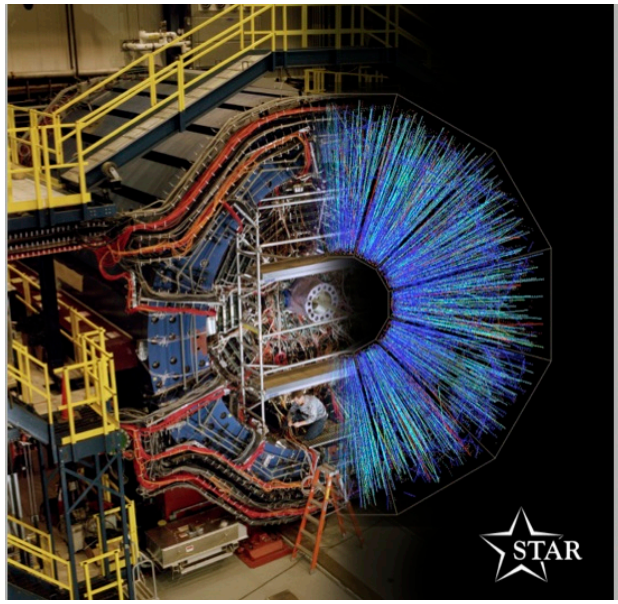
- 1965: Discovery of the cosmic background radiation: The Universe was exceedingly hot in its infancy.
- This raised the question about the state of matter at the highest temperatures.
- 1965: Hagedorn showed that the highest temperature at which matter can exist as hadrons is $T_H \approx 160$ MeV.
- In the late 1970s it became clear that the most likely form of matter at $T > T_H$ must contain “free” quarks and gluons; in other words, be a “quark-gluon plasma” (QGP).
- The two predominant challenges were:
  - How could a QGP be produced in the laboratory?
  - How could a QGP, once formed, be detected and investigated?

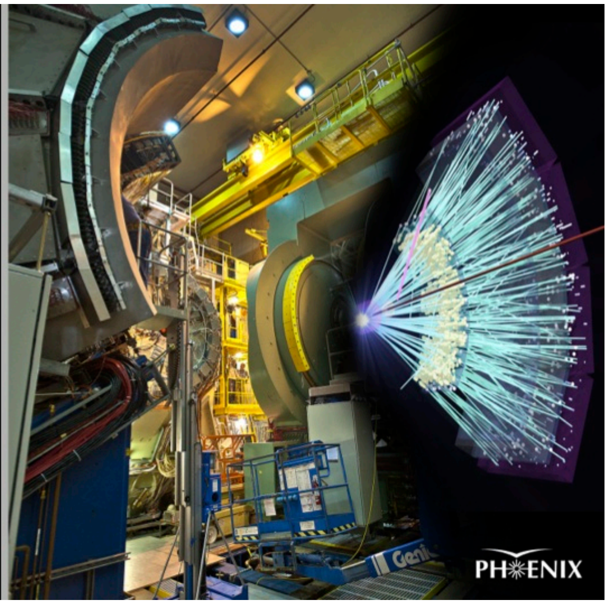
The Path to RHIC II

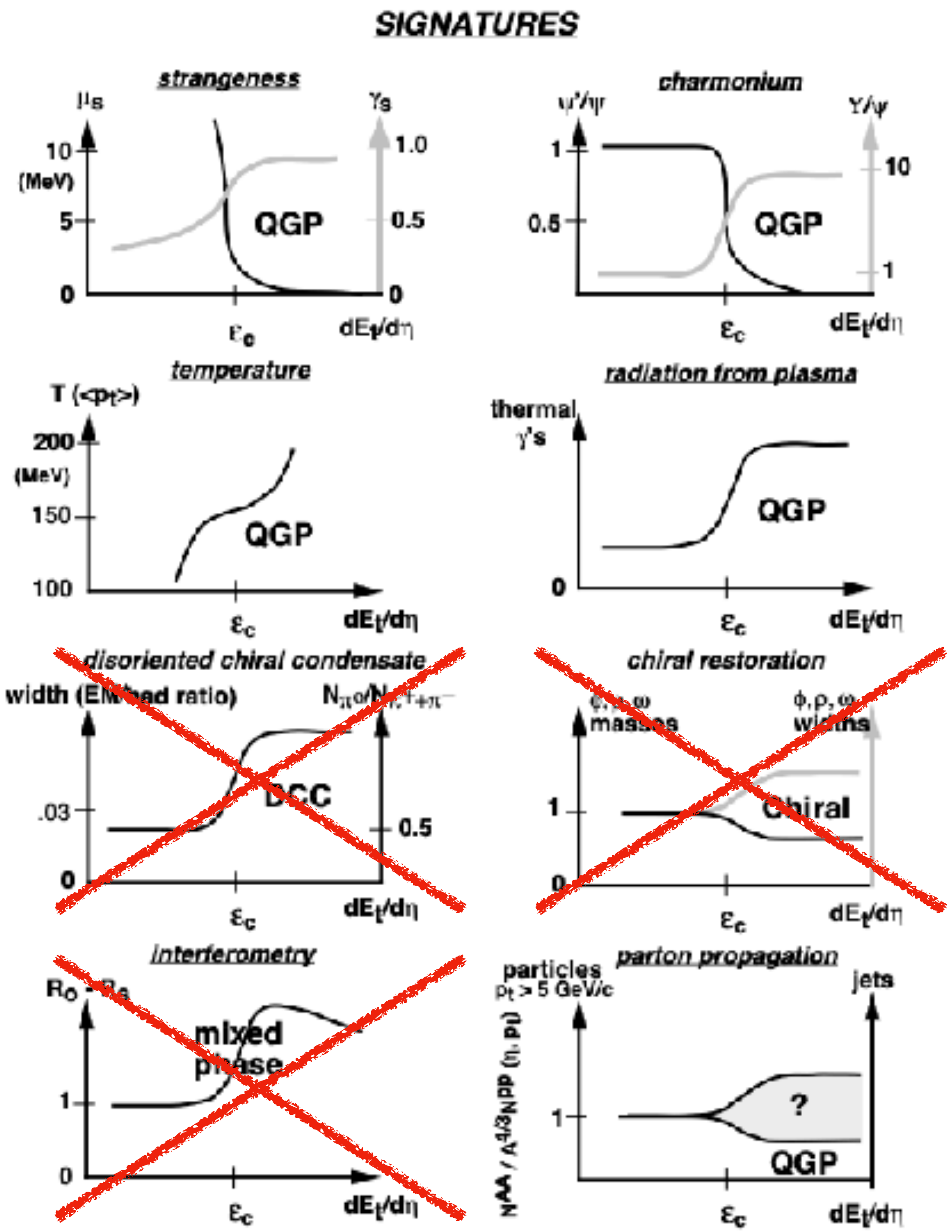
- Nuclear collisions were seen as the only viable path to create a QGP in the lab, but it was unclear how much CM energy was needed
  - European scientists embarked on using the existing CERN-SPS
  - U.S. scientists embarked on building a dedicated facility (RHIC) and undertook exploratory studies at the BNL-AGS
- Theorists went on wild speculations (as usual) proposing a multitude of QGP “signatures” (see next slide)
- Most nuclear physicists were extremely skeptical that any of the proposed signatures would be compelling
- The AGS/SPS experiments concluded with tantalizing hints, which motivated CERN to announce in February 2000 that “a new state of matter had been created” (DG Maiani)
- Many scientists remained skeptical.

RHIC: Machine - detectors - signatures









From: J. Harris & BM (1996)

BROOKHAVEN BULLETIN
Vol. 54 - No. 21 June 16, 2000
BROOKHAVEN NATIONAL LABORATORY

RHIC Begins World's Highest Energy Heavy-Ion Collisions

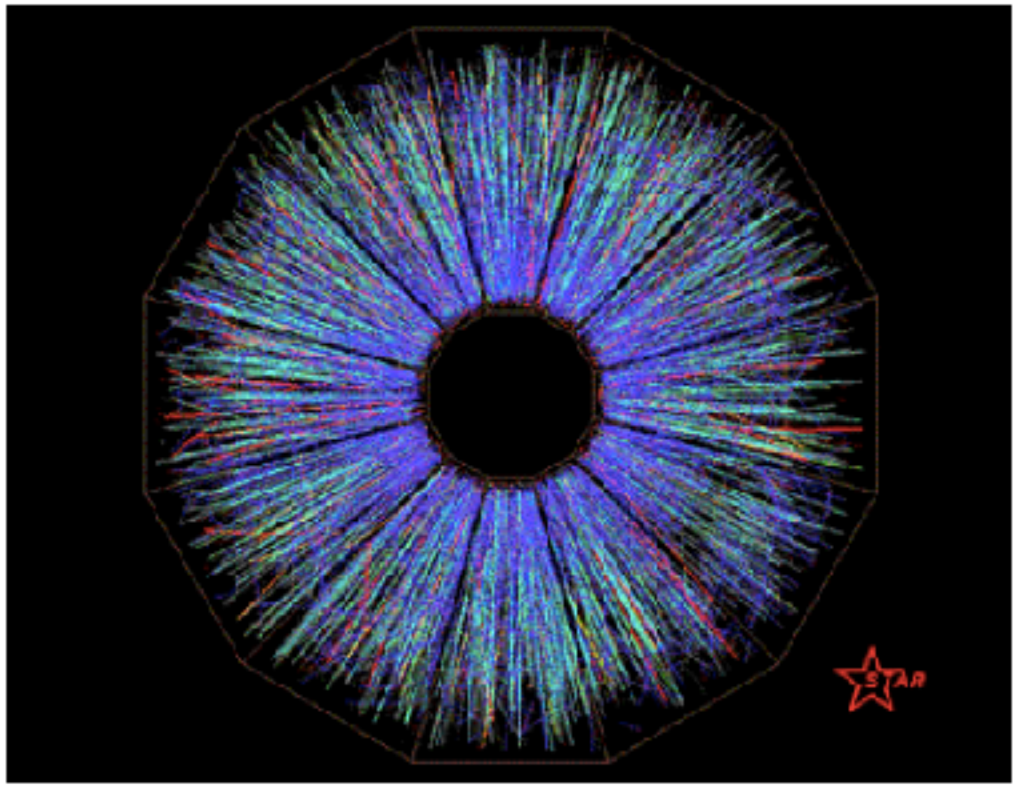
On the evening of Monday, June 12, operators in the main control room of the Relativistic Heavy Ion Collider (RHIC) watched control displays anxiously as the beams circulating in the collider's twin rings appeared to be colliding.

"The atmosphere was tense and very exciting," said Thomas Roser, head of the Accelerator Division and run coordinator for RHIC's first collision run. "We were operating at nearly 30 billion electron volts (GeV) per nucleon, our target energy for first collisions,

"We are crossing into a new frontier of scientific inquiry."

and we knew the beams were crossing at the collider's intersection points. But we couldn't say for sure that we'd had collisions until we got definitive, corroborative evidence from the detectors."

All four of RHIC's detectors — BRAHMS, PHENIX, PHOBOS and STAR — were poised and ready to take data as the accelerator physicists began to steer the beams into collision, necessarily one detector at a time.



A view of a RHIC collision seen in the STAR detector. "We knew immediately that we'd seen a true, beam-on-beam collision because all the particle tracks clearly originated at the center of the beam tube and sprayed out in all directions," said John Harris of Yale University and head of the STAR team. The symmetric pattern of particle tracks contrasts dramatically with so-called background events the team had witnessed, where collisions between ions and gas particles in the beam tube produce tracks going in only one direction.

est and biggest particle accelerator for studies in nuclear physics. "We are crossing into a new frontier of scientific inquiry," said Energy Secretary Bill Richardson upon hearing of the first collisions. "Scientists from around the world will use this facility to answer some of the most basic questions about the properties of matter and the evolution of our universe."

The collider aims to recreate the conditions of the early universe to gain insights into the fundamental nature of matter — and extend the boundaries of scientific understanding through the 21st century and beyond.

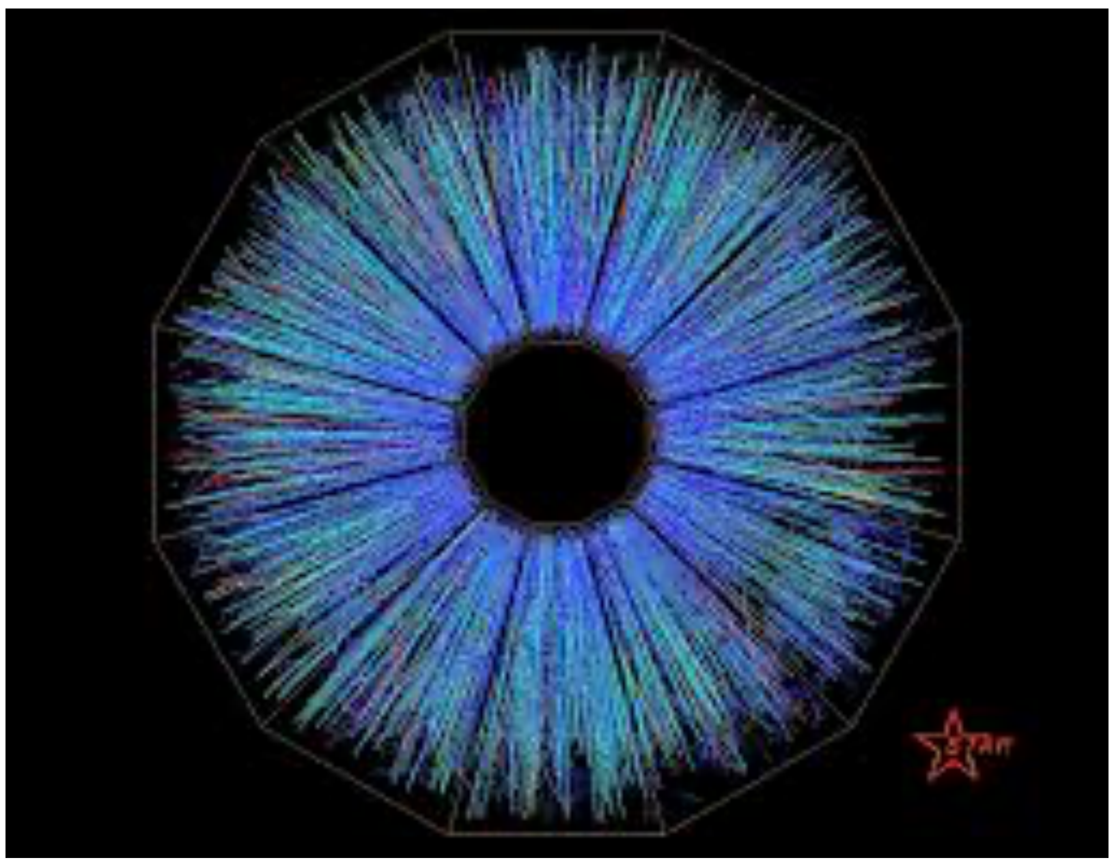
Scientists will use data collected during the collisions to explore the particles known as quarks and gluons

The high temperatures and densities should allow a soup-like plasma, a state of matter believed to have last existed millionths of a second after the

Moving fast…

June 12, 2020

First Au+Au collision at STAR



July 19, 2020

PHOBOS Collaboration Presents First Physics Results From RHIC

The first physics results from the initial collisions at BNL's Relativistic Heavy Ion Collider (RHIC) were presented by the PHOBOS collaboration to a full house at Berkner Hall on July 19.

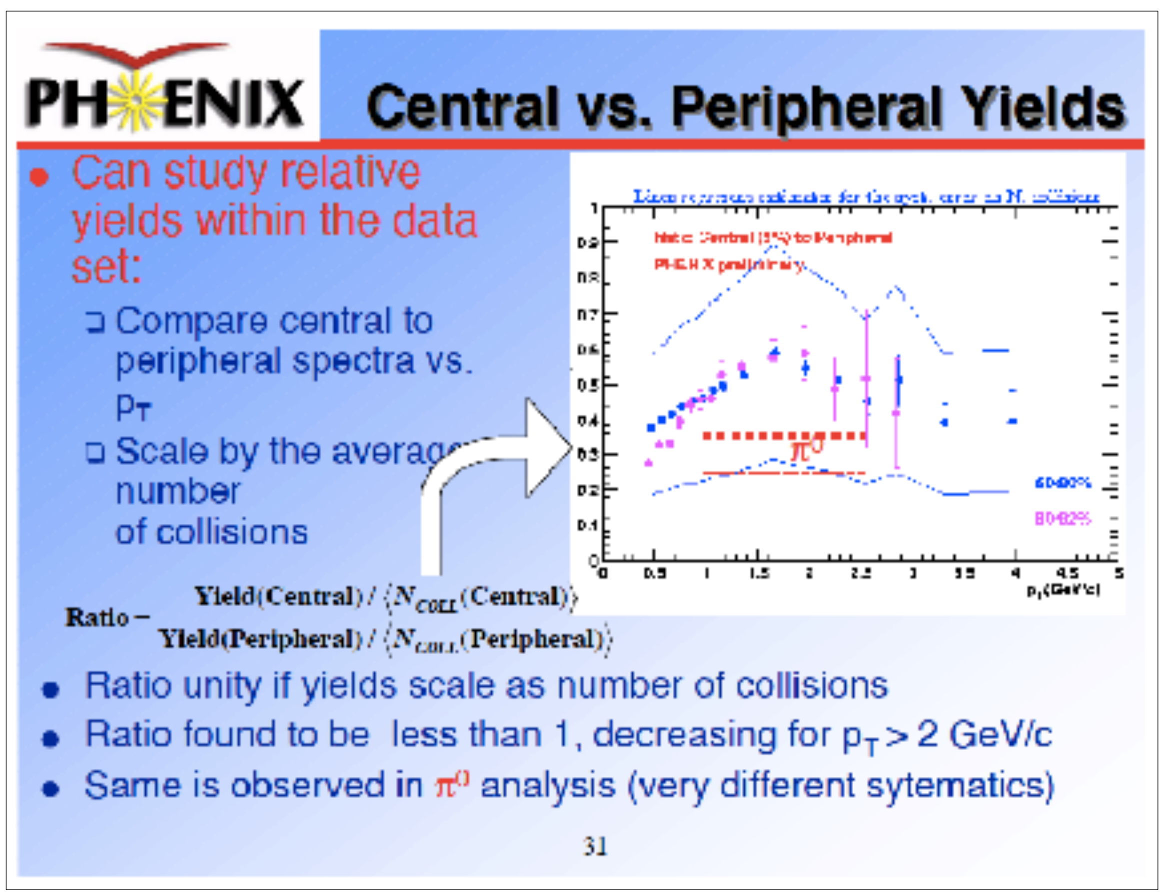
collisions. At the higher energy, the collisions achieved an energy density 50 percent higher than that observed for lead-lead collisions at CERN, the European particle physics laboratory."

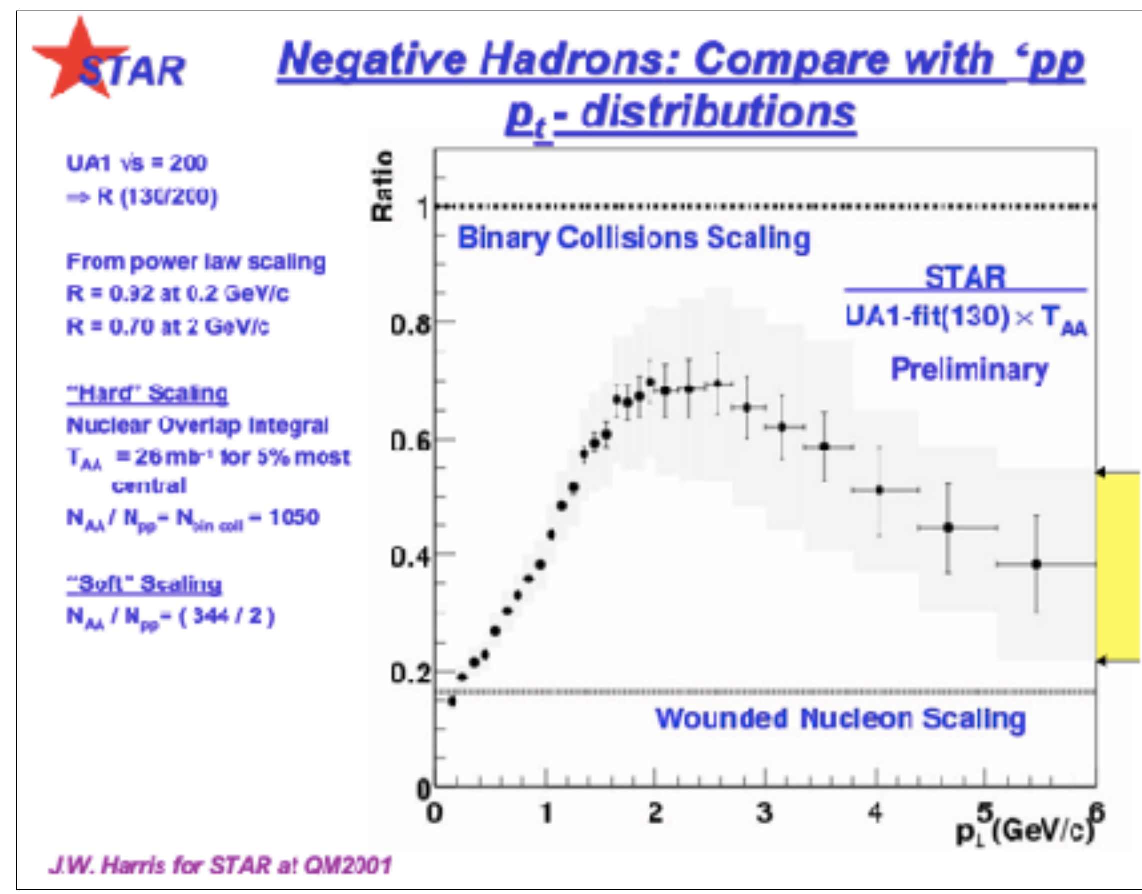
As Busza explained, data for the

January 2021 - I

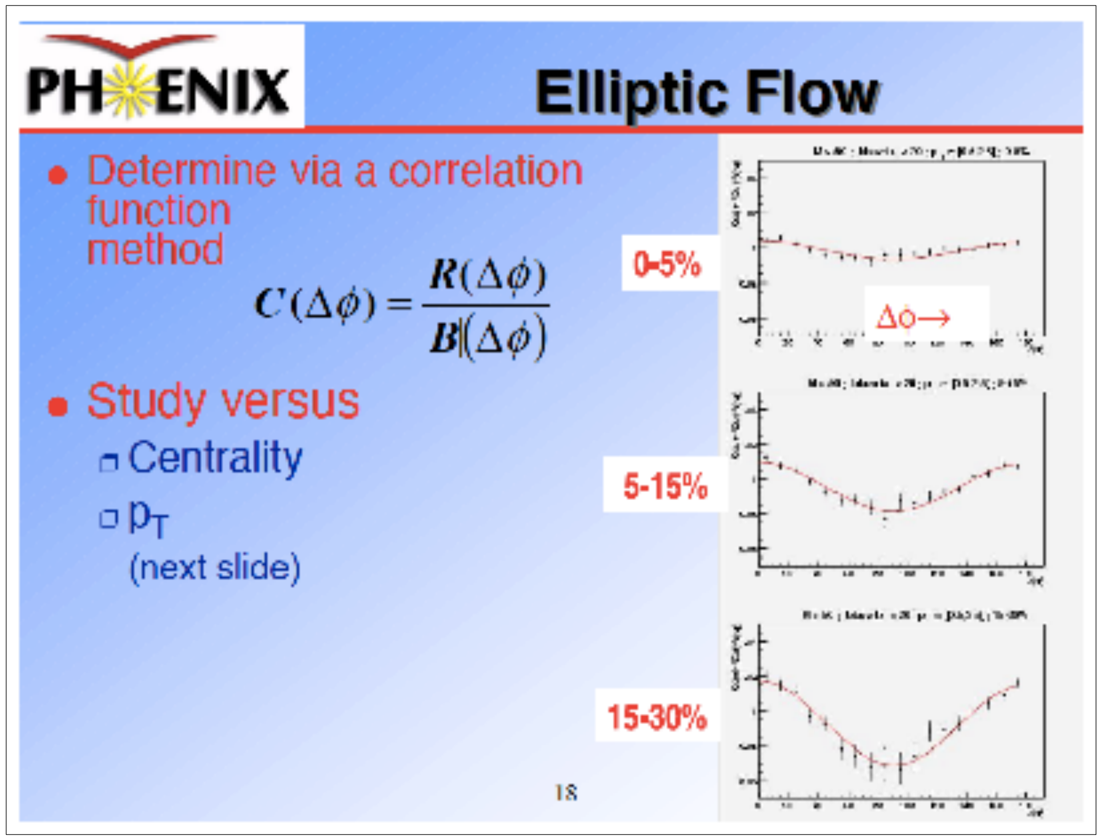
A conference remembered for superb science and lousy food

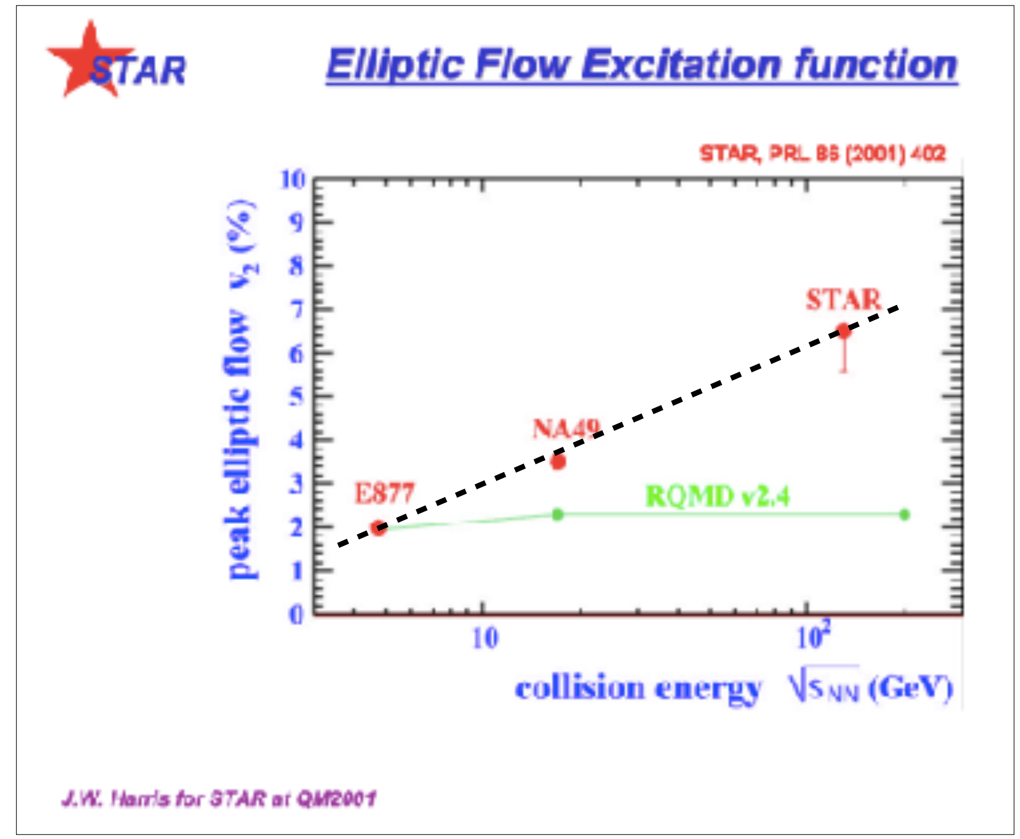
Jet Quenching





January 2001 - II

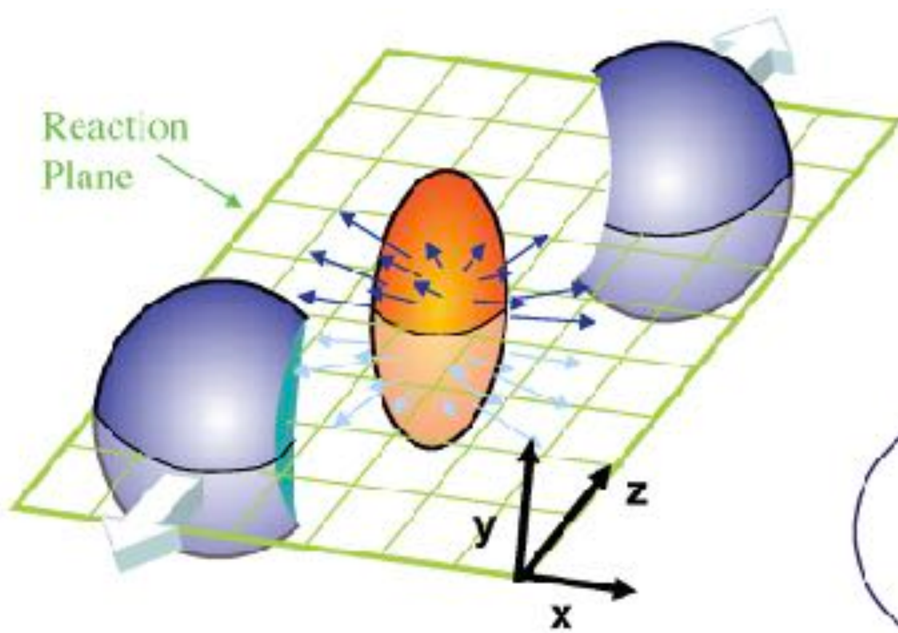




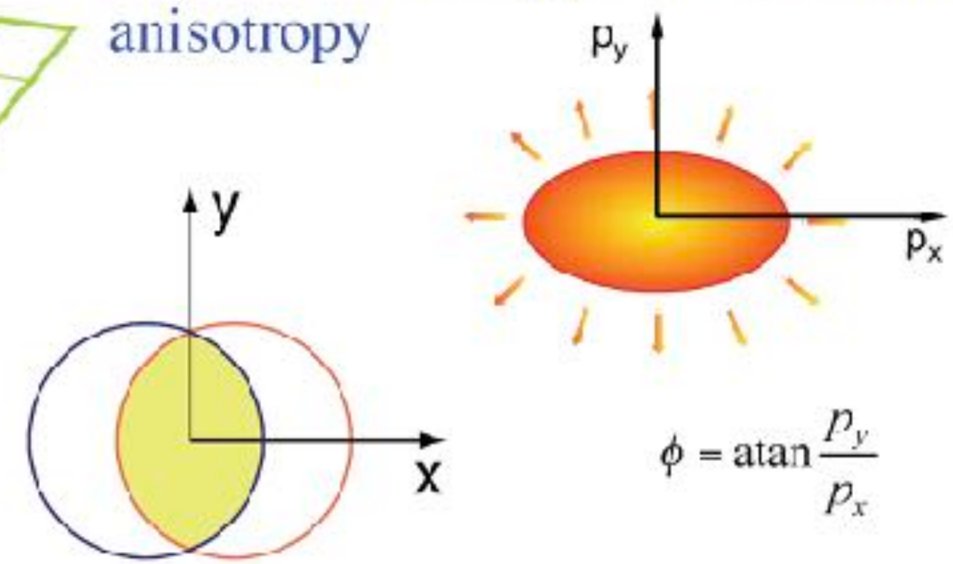
Geometry

⇓

Flow



- spatial anisotropy ⇒ momentum anisotropy



The NYT asks - RHIC responds

On the Verge of Re-Creating Creation. Then What?

New York Times - Week In Review, Jan. 28, 2001

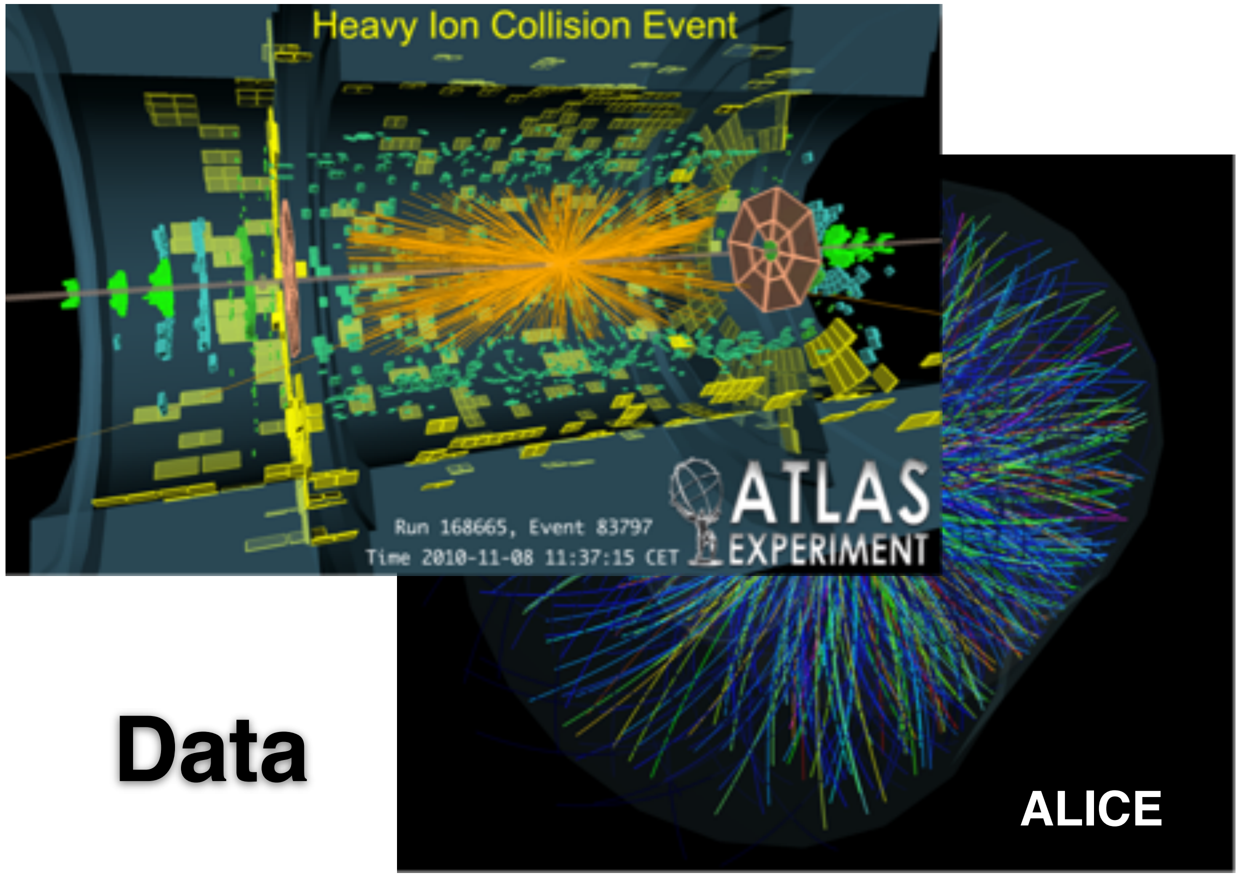
RHIC Scientists Serve Up 'Perfect' Liquid

New state of matter more remarkable than predicted — raising many new questions

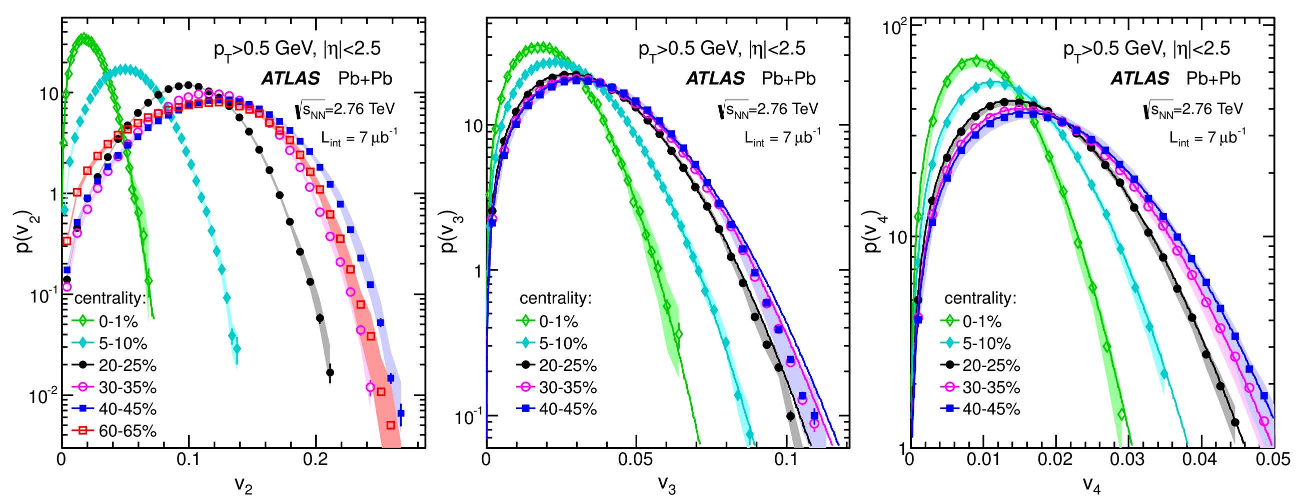
April 18, 2005

TAMPA, FL — The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) — a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory — say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid.*

In fact, the first non-superfluid whose specific viscosity is near the quantum bound.

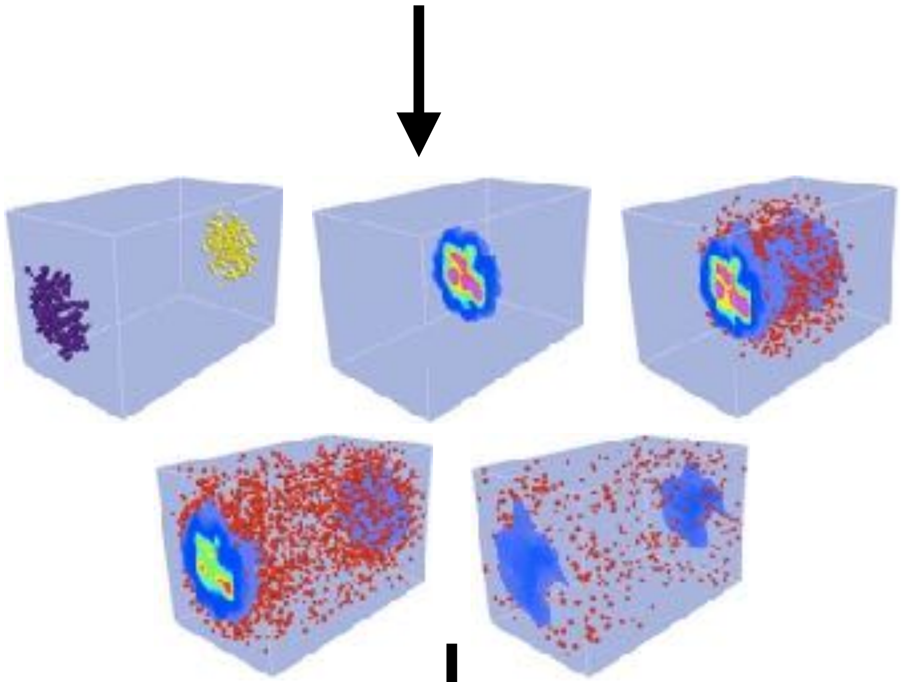


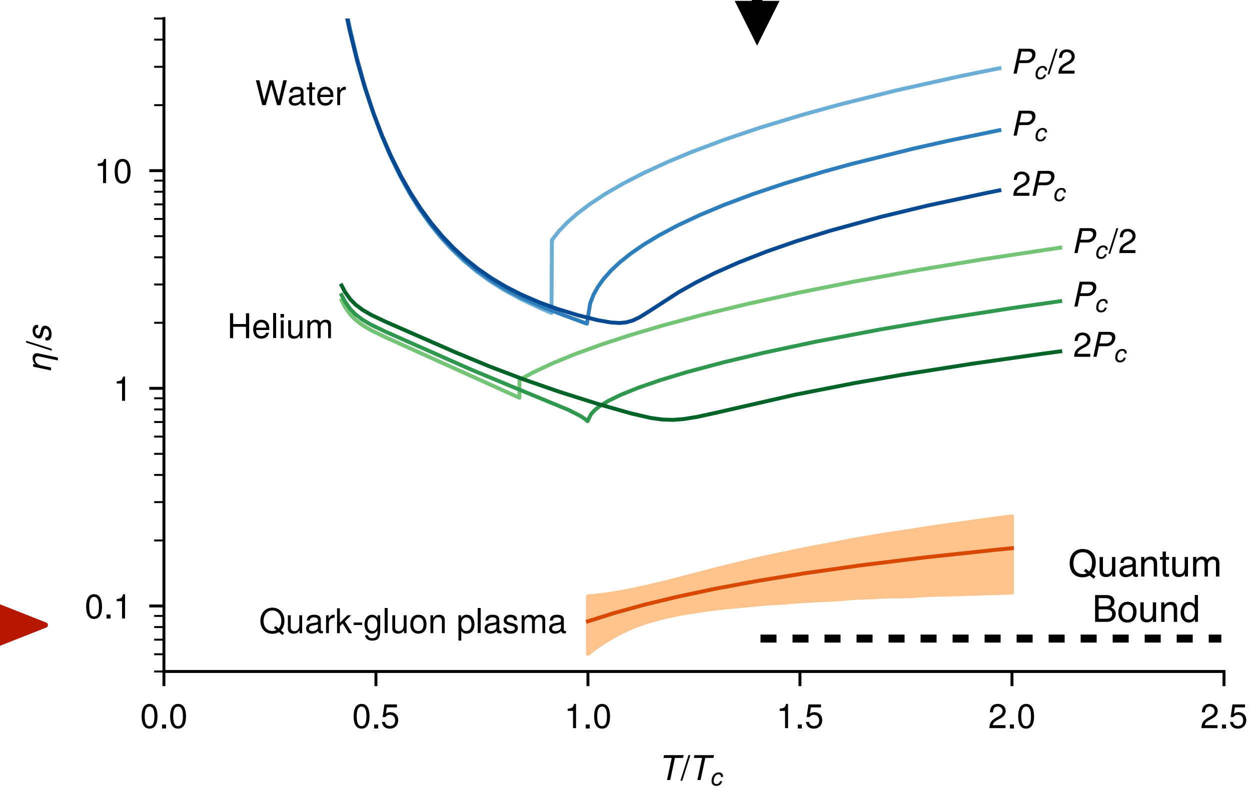
Data



Model

initial conditions, model parameters

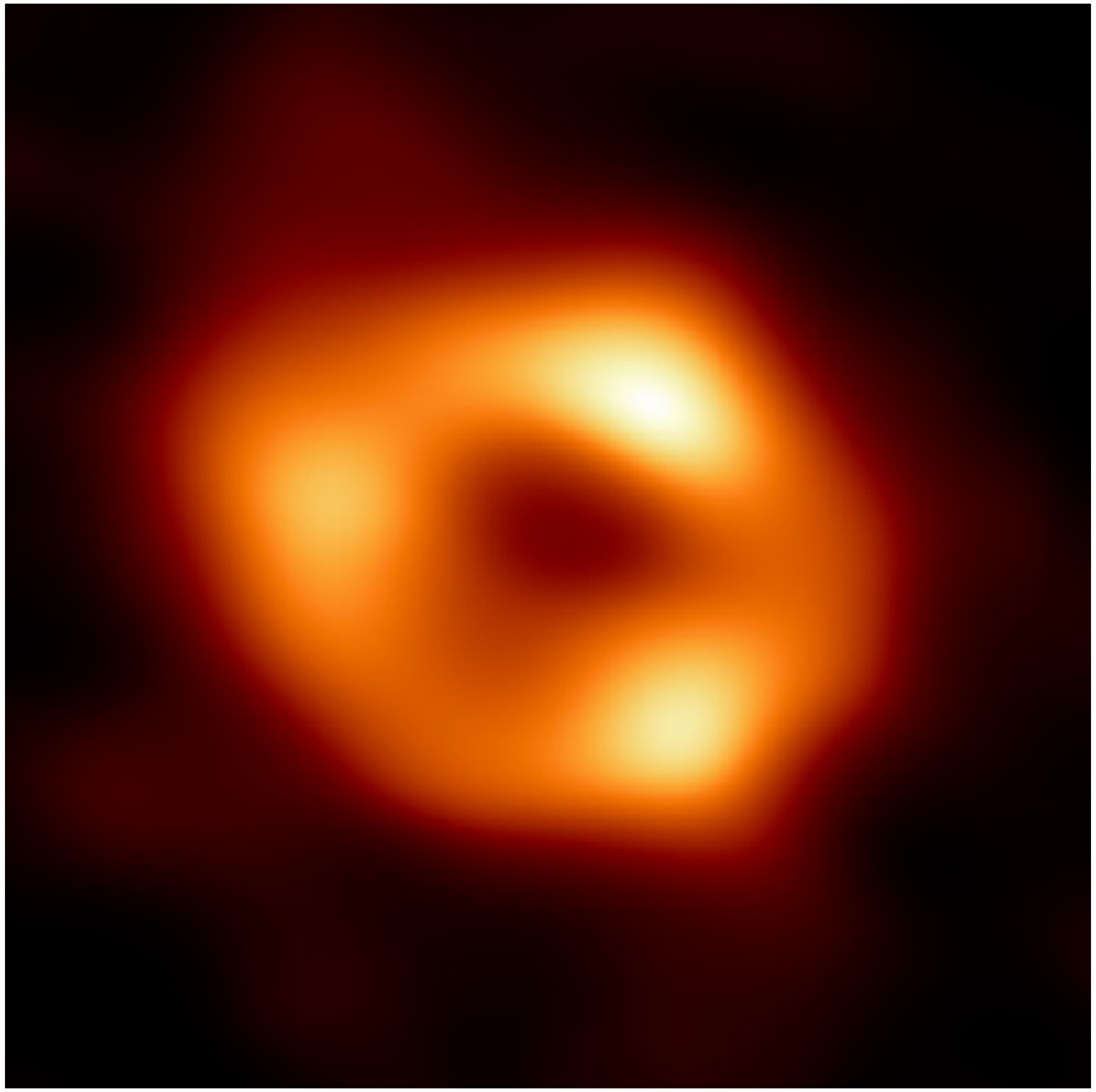




Model-data comparison using state-of-the-art Markov-Chain Monte-Carlo & Bayesian inference

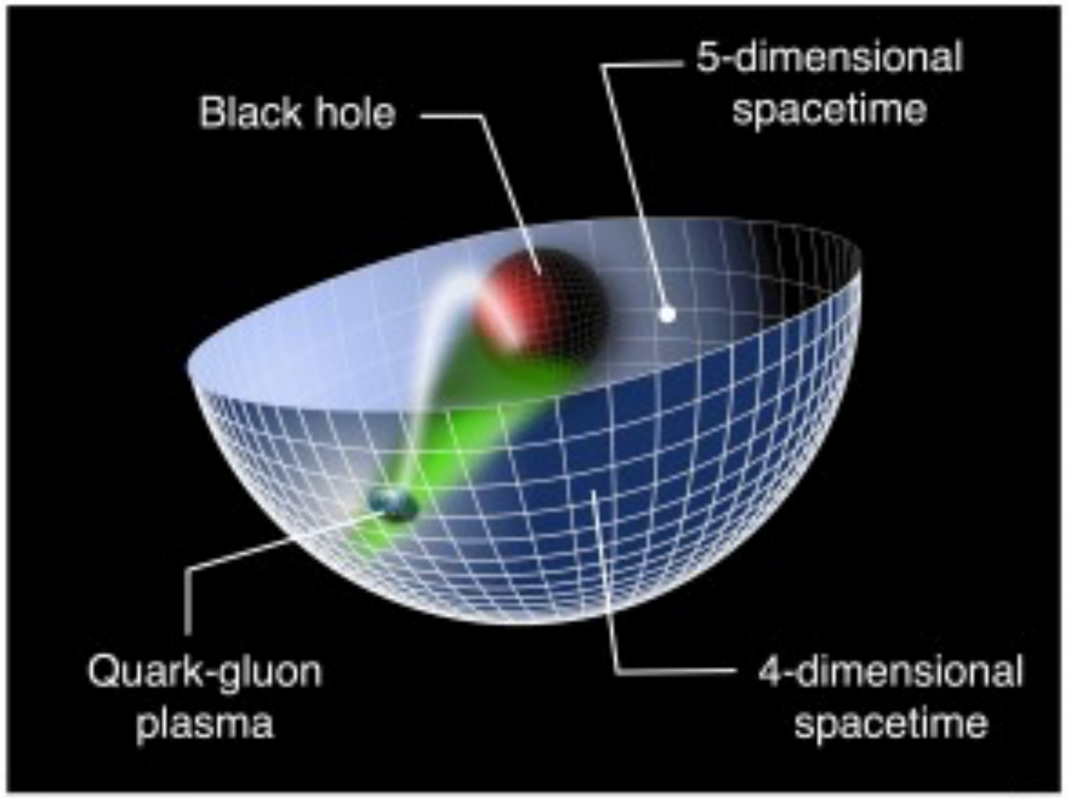
J.E. Bernhard, et al., *Nature Phys.* 15 (2016) 1113

The BH Paradigm



Black Hole at the center of the Milky Way imaged by the Event Horizon Telescope

Space-time near the event horizon of a Black Hole behaves like a viscous relativistic fluid with shear viscosity $\eta = s/4\pi$. Analogy becomes manifest in holographic models with a 5-dim. gravity dual of a 4-dim. gauge theory.



QGP: Signatures & Diagnostics

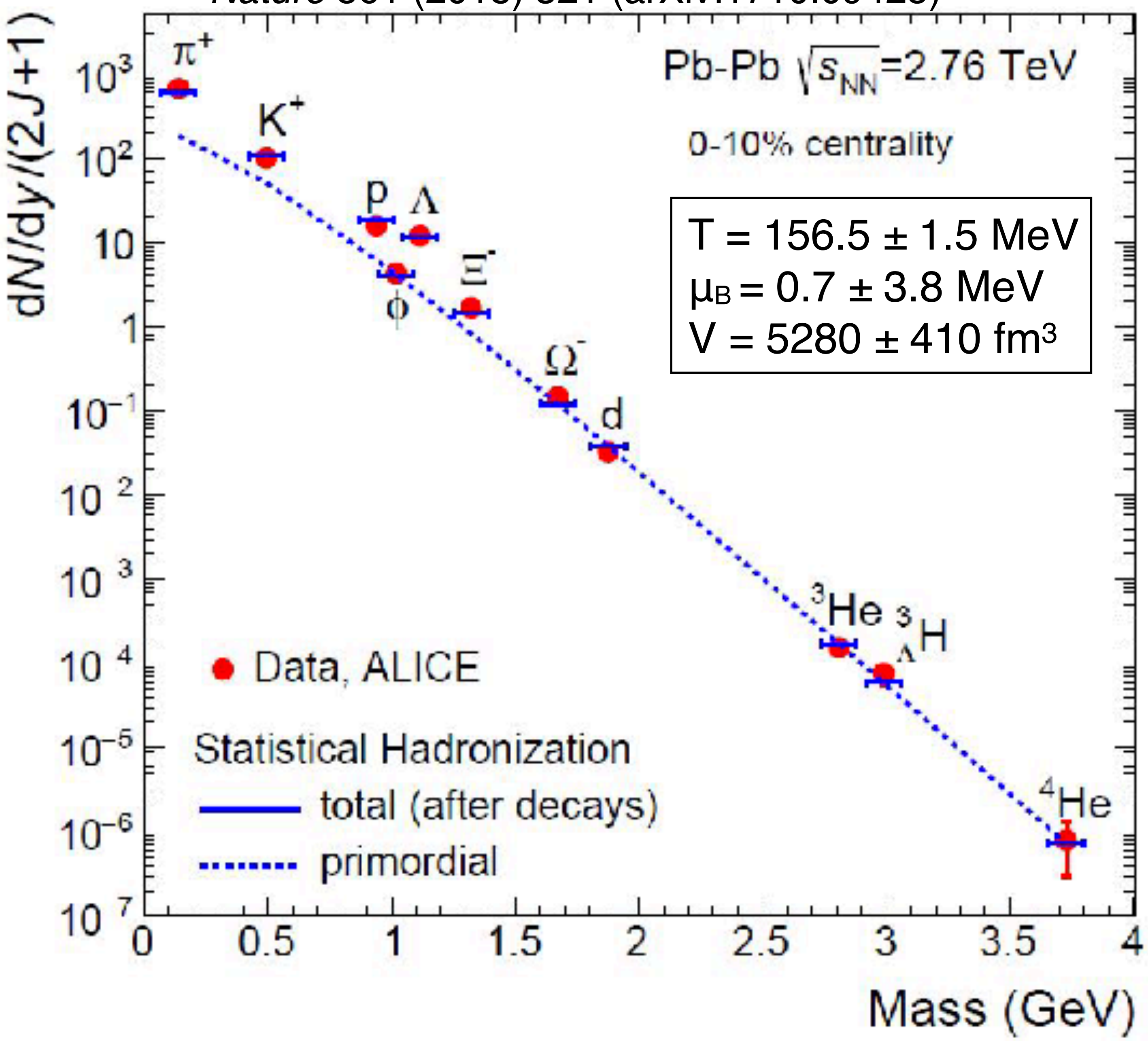
- ***QGP Signatures*** probe *salient characteristics* of the QGP:
  - Quark / gluon deconfinement (percolation)
  - Color screening
  - Chiral symmetry restoration
- ***QGP Diagnostics*** probe the *physical properties* of the QGP:
  - Thermodynamic properties
  - Structural properties
  - Transport properties
- The predominant challenge is that the QGP formed in heavy ion collisions does not exist in controlled environment, but is itself a dynamically evolving system:
  - **All observables require interpretation in the framework of transport models**

QGP Diagnostics: Many tools

- Collective flow: Equation of state $\varepsilon(T)$, $P(T)$, $s(T)$, η, ζ
- Hadrochemistry: Flavor equilibration
- Hadronization at the phase boundary: quark recombination
- Color screening: J/ψ and Υ "melting" ($Q\overline{Q}$ suppression)
- Energy loss of energetic partons (jet quenching)
- Hyperon polarization: vorticity
- Fluctuations of conserved quantities can probe for the nature of the transition from hadron gas to QGP
- …..

Statistical hadronization

Andronic, P. Braun-Munzinger, K Redlich, J. Stachel,
Nature 561 (2018) 321 (arXiv:1710.09425)



After accounting for decays:

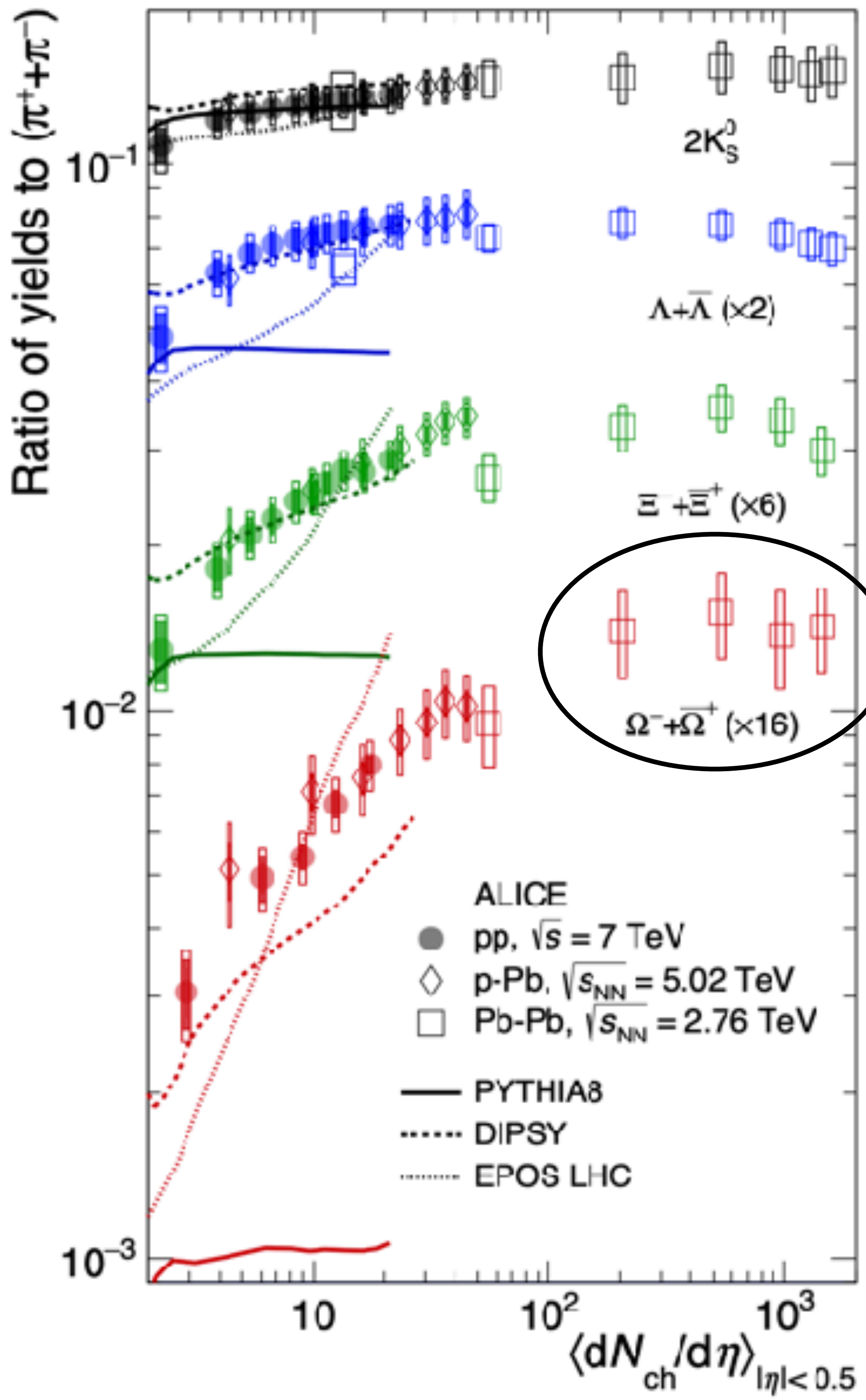
All hadrons produced in HRG chemical equilibrium in Pb+Pb at a fixed temperature *T*

Natural explanation: Transition from unconfined (percolating) quarks to confined quarks

No *Strangeness* penalty factor:

Even the weakly bound hyper-triton ($^3_\Lambda$H) follows the universal statistical (thermal) law.

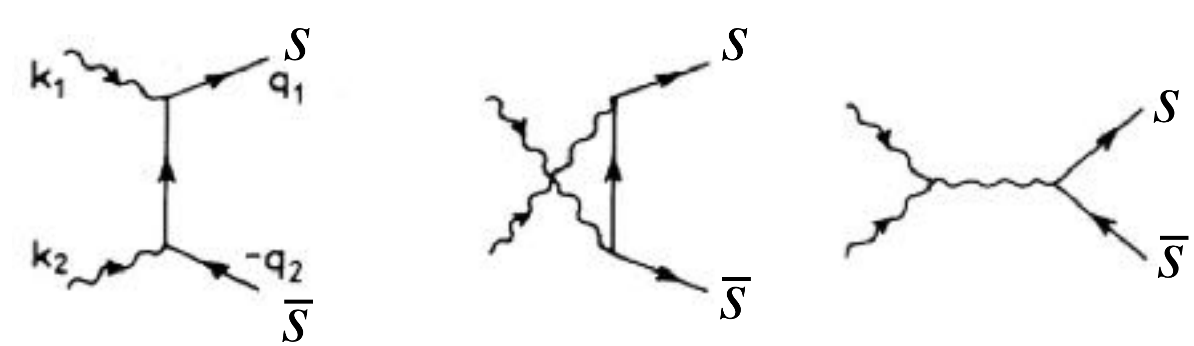
Multi-strange baryons



Strangeness enhancement:

- Grows with size / life-time
- No strangeness penalty observed in large systems!

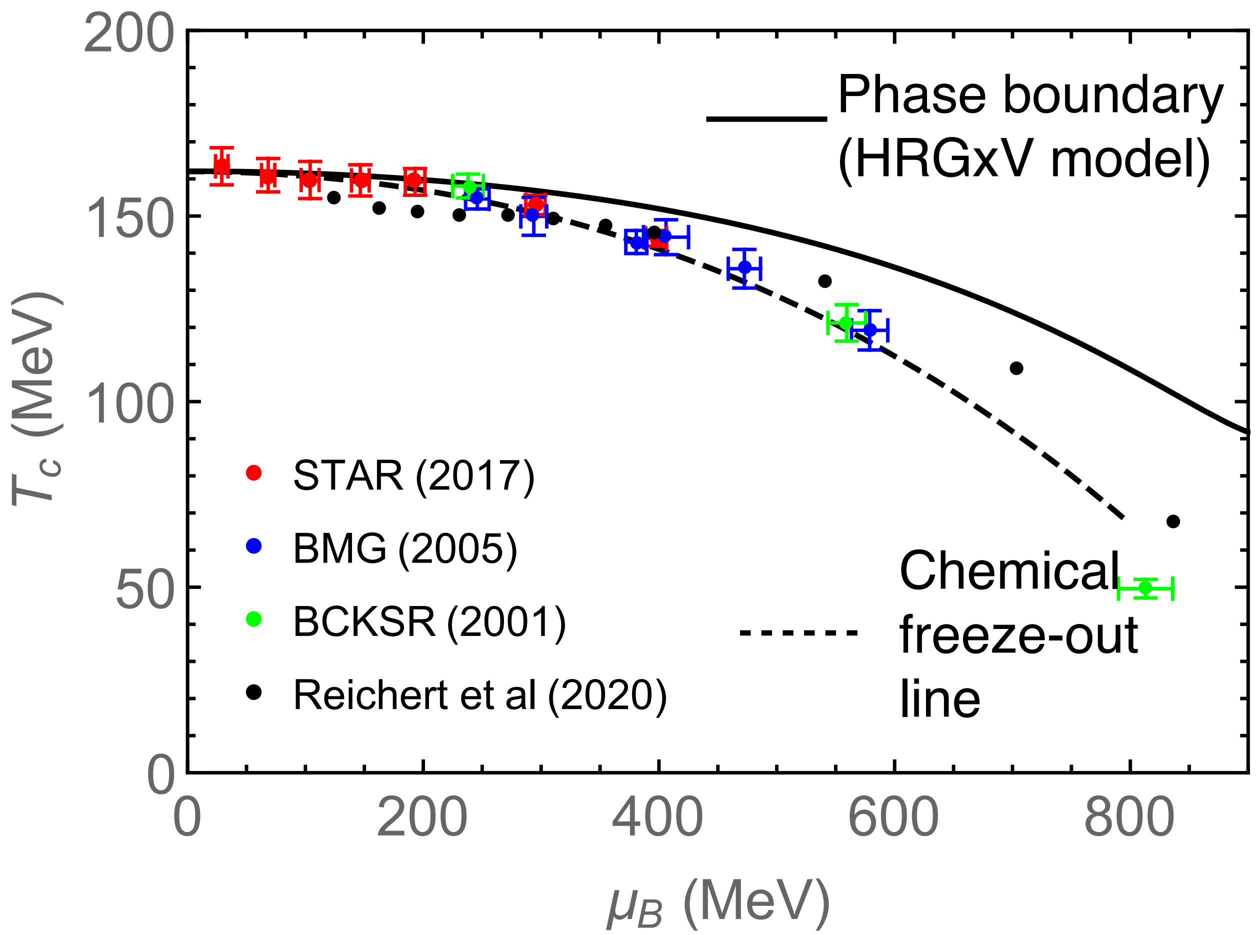
Gluon reactions establish $s/\bar{s}$ equilibrium in the QGP, which then translates to equilibrium yields of multi-strange hadrons.



$$\left.\begin{array}{l}\bar{s} + Ⓢ \\ \bar{s} + Ⓢ \\ \bar{s} + Ⓢ\end{array}\right\} \rightarrow (sss) = \Omega$$

"Yes -
it's a QGP!"

Chemical freeze-out



Chemical freeze-out line tracks close to the phase boundary, but represents different physics:

- $T_{\rm ch}(\mu_B)$ encodes kinetic physics
- $T_c(\mu_B)$ encodes thermal physics

Their relation depends on velocity of fireball expansion relative to chemical reaction rates among hadrons

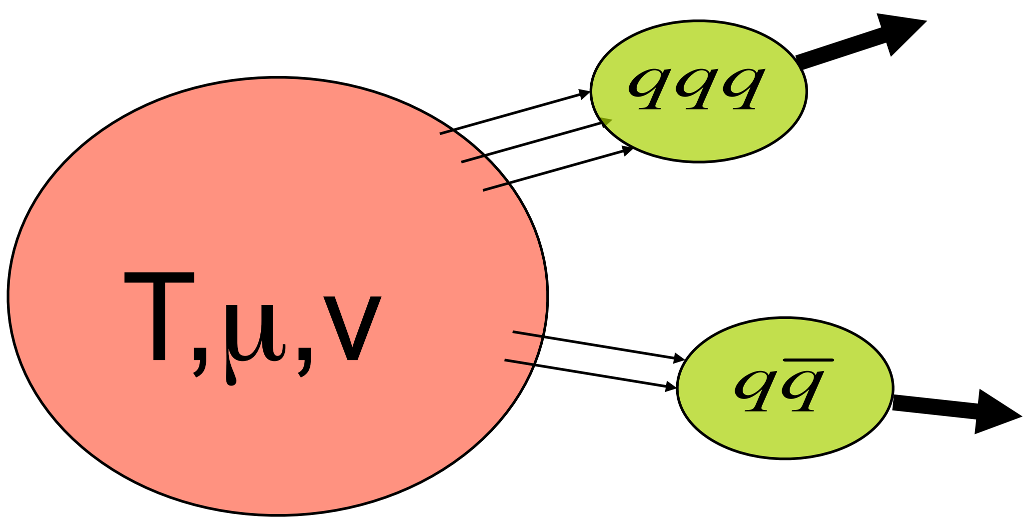
Chemical freeze-out at or just below phase boundary is consistent with quarks being unconfined (percolating) in the QGP.

“Ultimate” test possible with multi-charm hadrons….

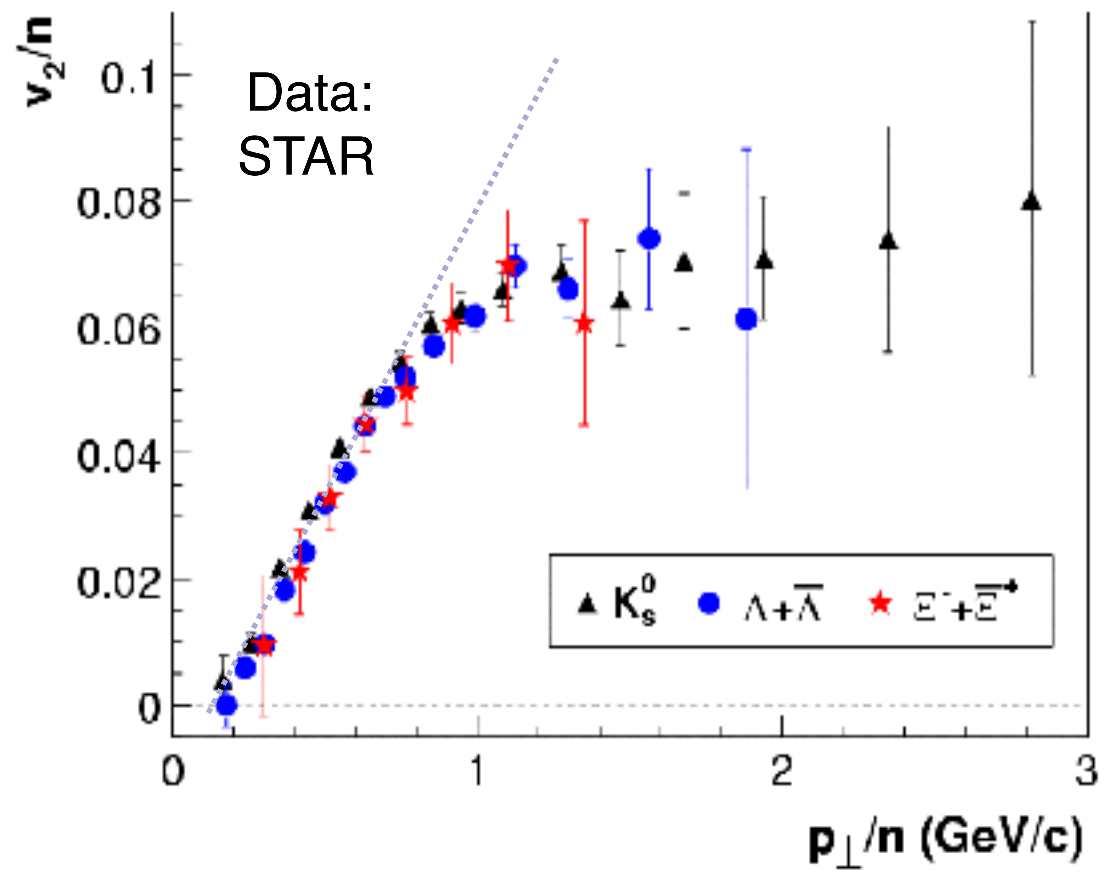
Quark number scaling

In the recombination picture, meson and baryon $v_2(p_T)$ follow from quark $v_2(p_T)$:

$$v_2^{\mathrm{M}}(p_{\mathrm{T}}) = 2\ v_2^{\mathrm{q}}(p_{\mathrm{T}}/2) \qquad v_2^{\mathrm{B}}(p_{\mathrm{T}}) = 3\ v_2^{\mathrm{q}}(p_{\mathrm{T}}/3)$$



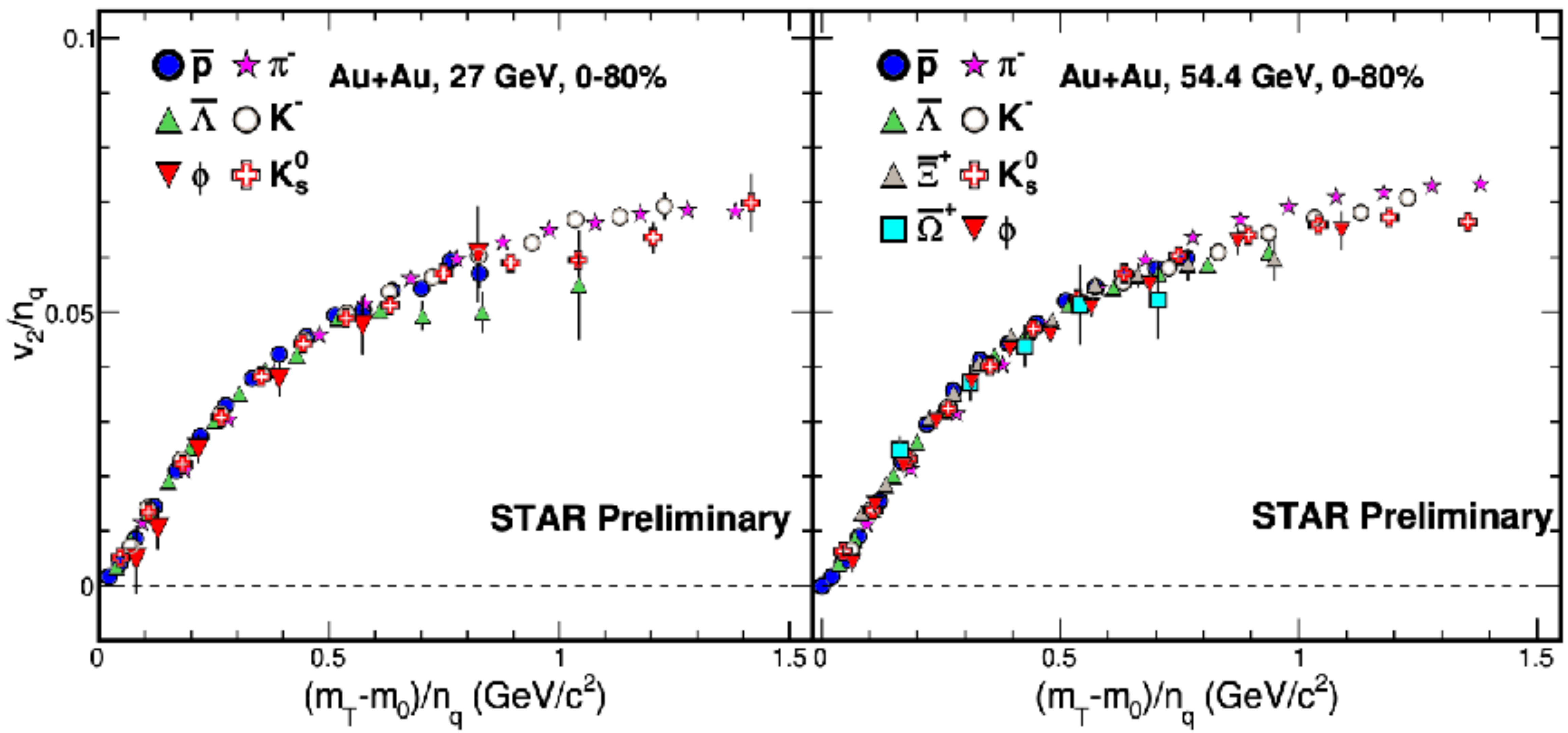
Emitting medium is composed of deconfined, flowing quarks.



R.J. Fries, V. Greco, P. Sorensen, *Annu. Rev. Nucl. Part. Sci.* 58 (2008) 177

Valence quark scaling

Remarkable persistence of valence quark scaling of elliptic flow established over a wide range of collision energies, from $\sqrt{s_{NN}}$ = 27 GeV to 2.76 TeV showing that collective flow originates at the quark level: “Yes - it’s a QGP!”



Color screening

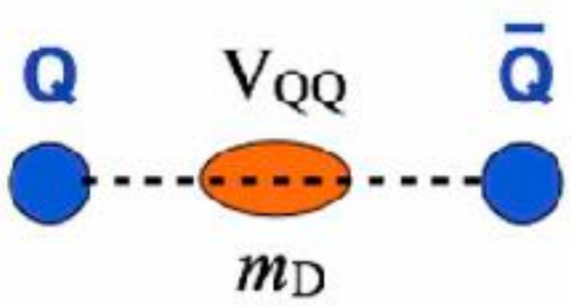
Static color fields are screened in the QGP

- Quarkonia "melt" when screening length < radius
- Melting threshold depends on heavy quark mass and binding energy

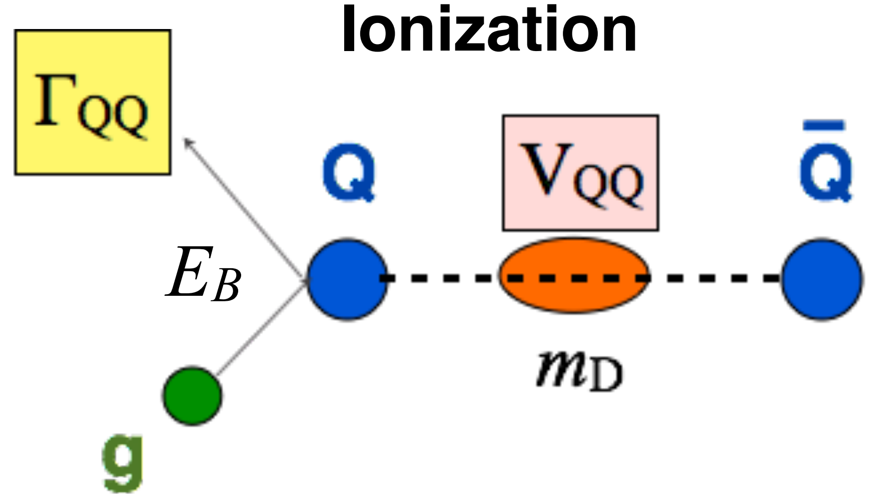
Dynamical description needs to account for:

- Color screening ($Q-\overline{Q}$ potential becomes short-ranged)
- Thermal ionization
- Regeneration by $Q\overline{Q}$ recombination in QGP or at hadronization

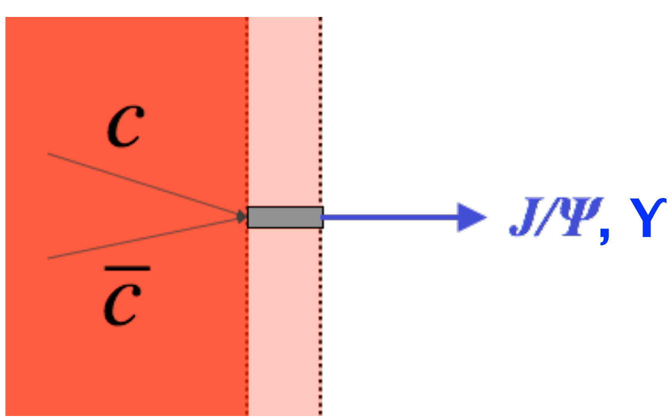
Color screening



Ionization

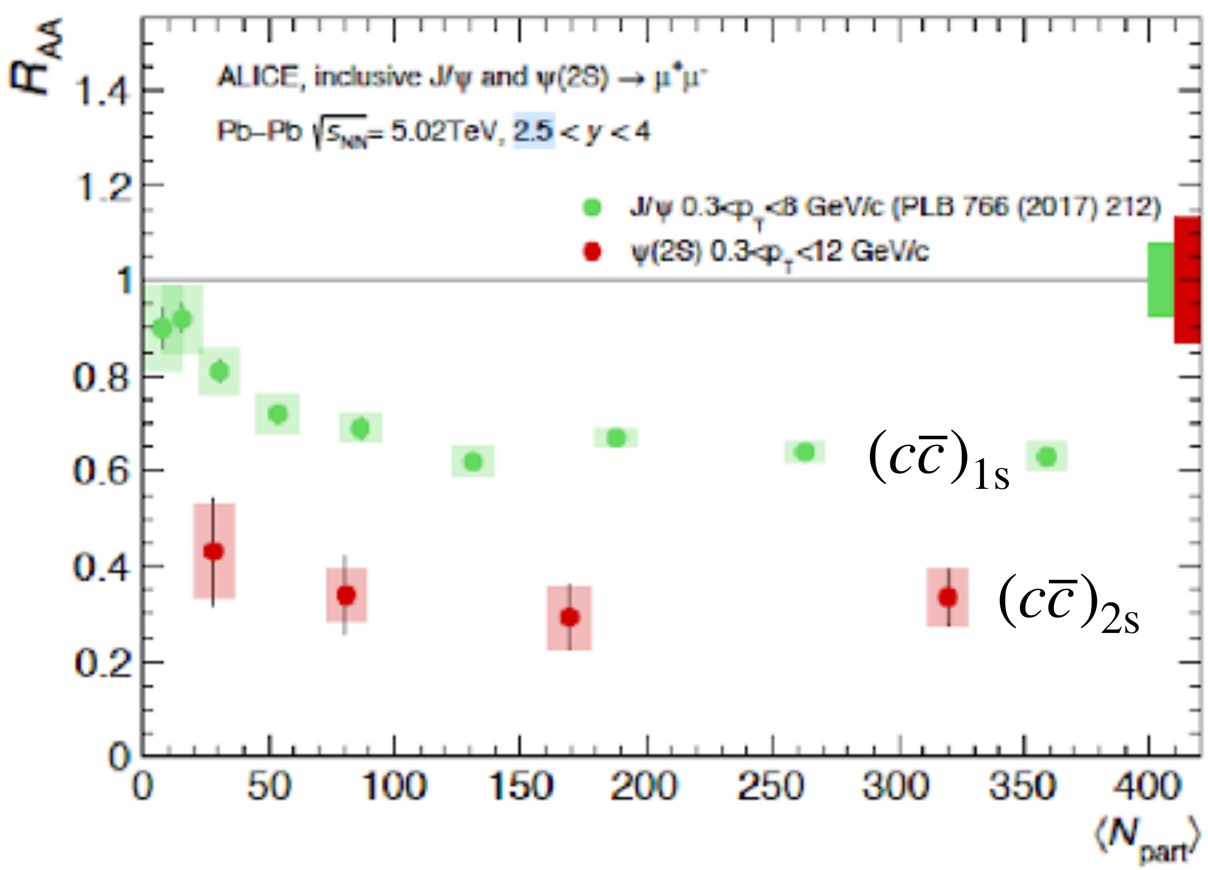


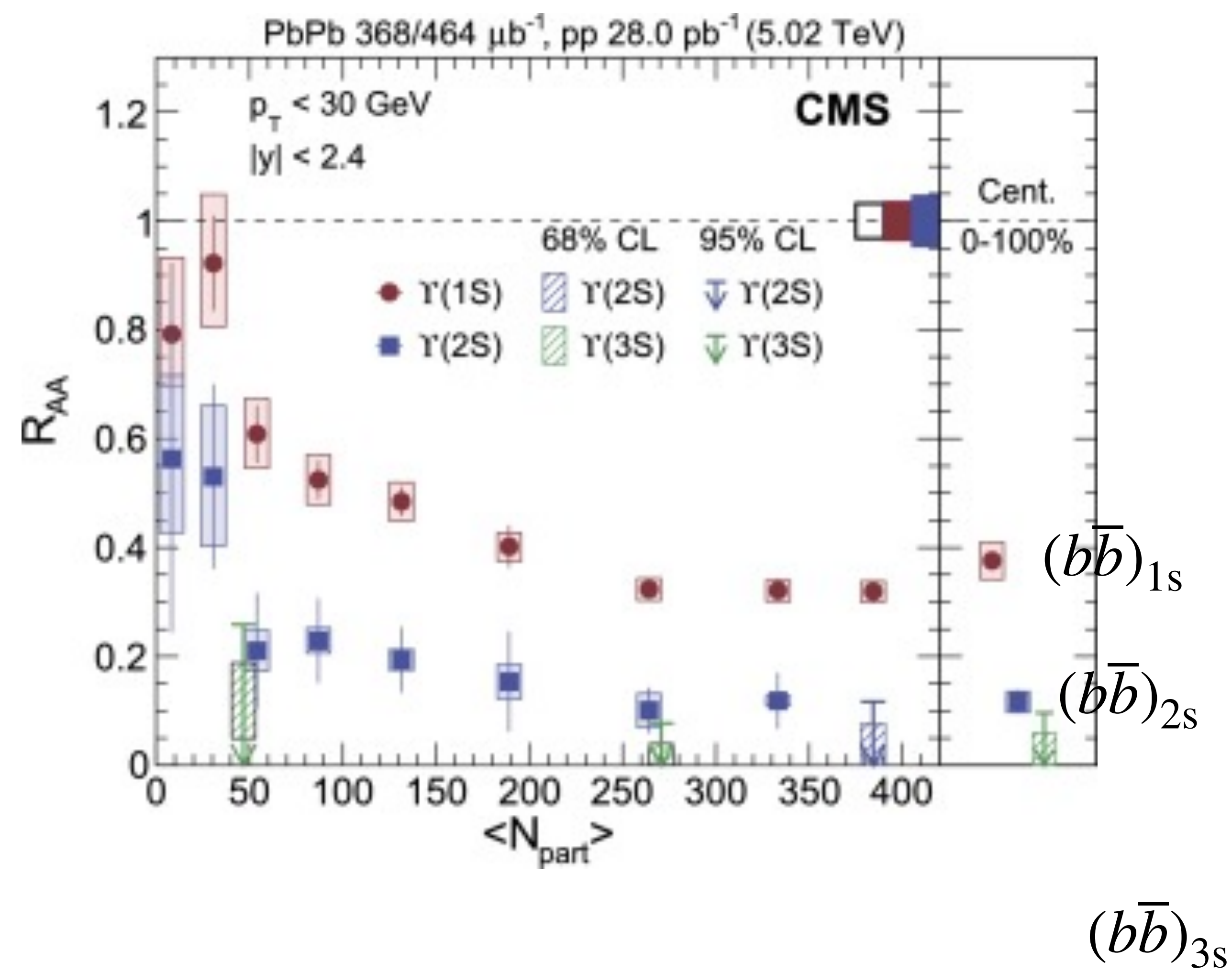
Recombination



Quarkonium suppression

All data from RHIC and LHC is consistent with the principle of "sequential" melting: Less bound states are suppressed first and more strongly: "Yes - it's a QGP!"





Hard QCD Probes

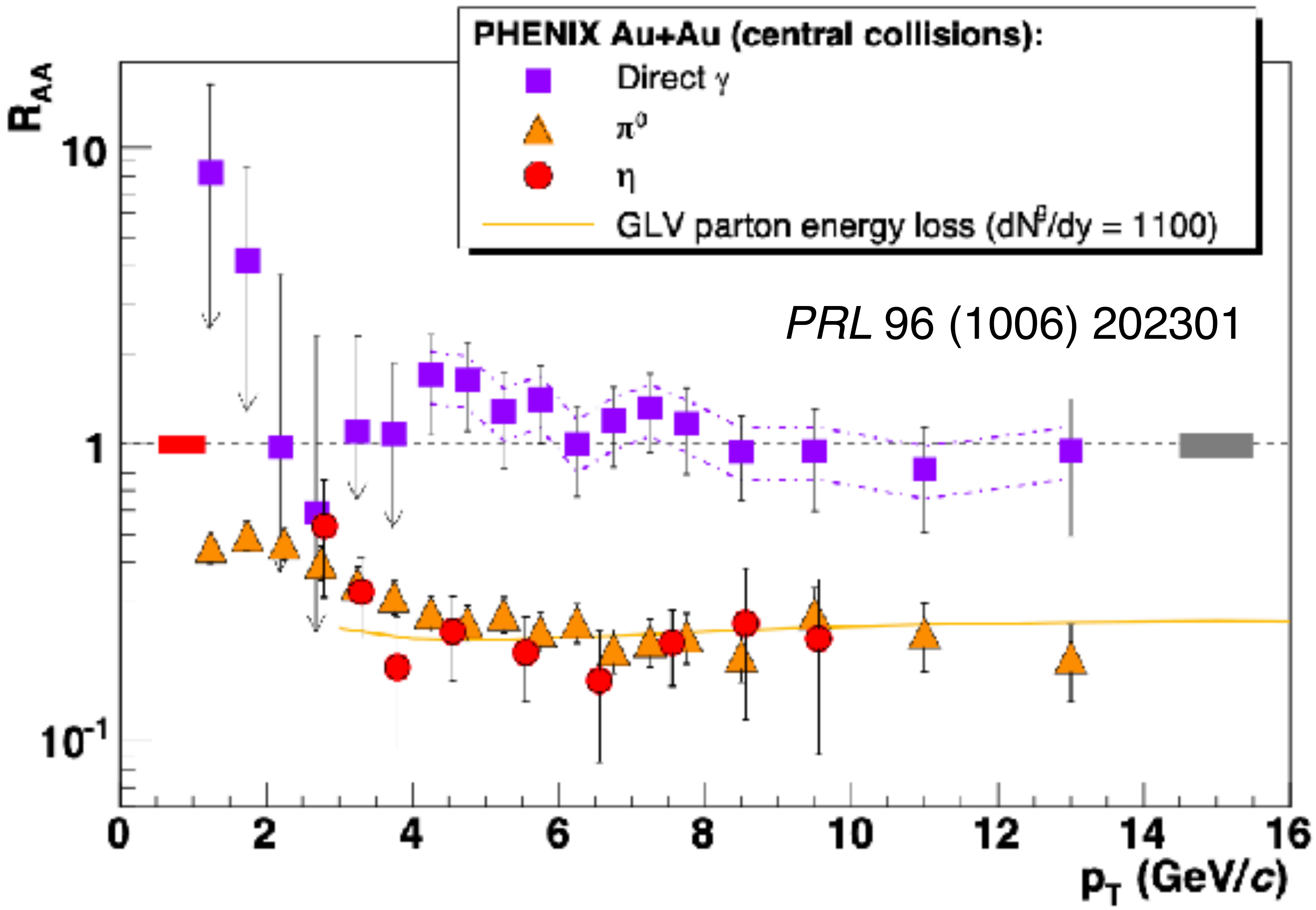
Hard probes (calculable in pQCD) are measured relative to their yields in p+p

Nuclear suppression factor:

$$R_{AA}(p_T) = \frac{d^2N_{AA}/dp_T dy}{\langle T_{AA}\rangle \cdot d^2\sigma/dp_T dy}$$

Measured

Avg. number of binary NN collisions per area (calculated)

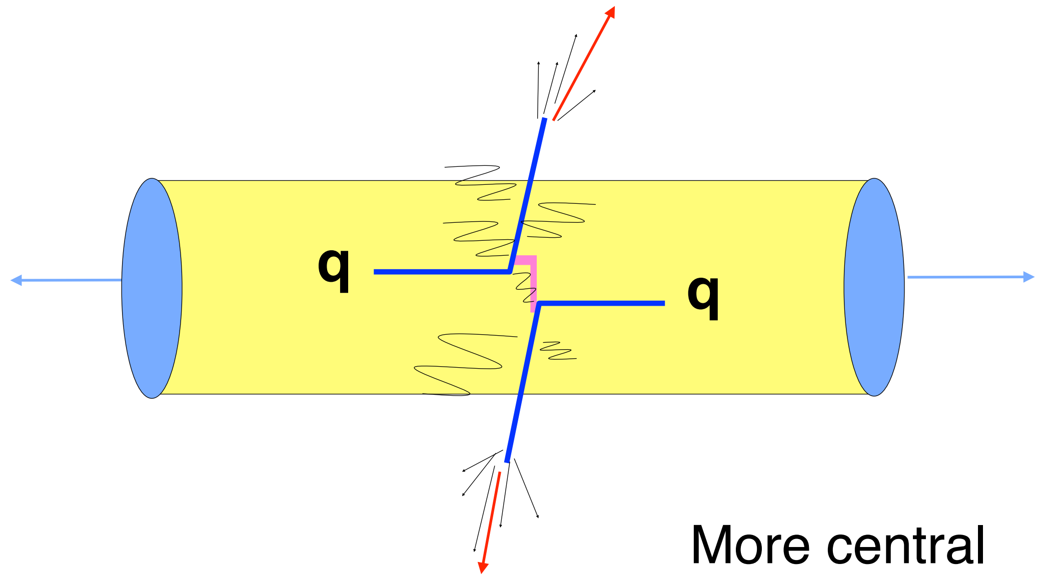


PRL 96 (1006) 202301

Probes that are unaffected by the nuclear medium must show $R_{AA} = 1$.

Examples: γ, Z^0

Jet quenching

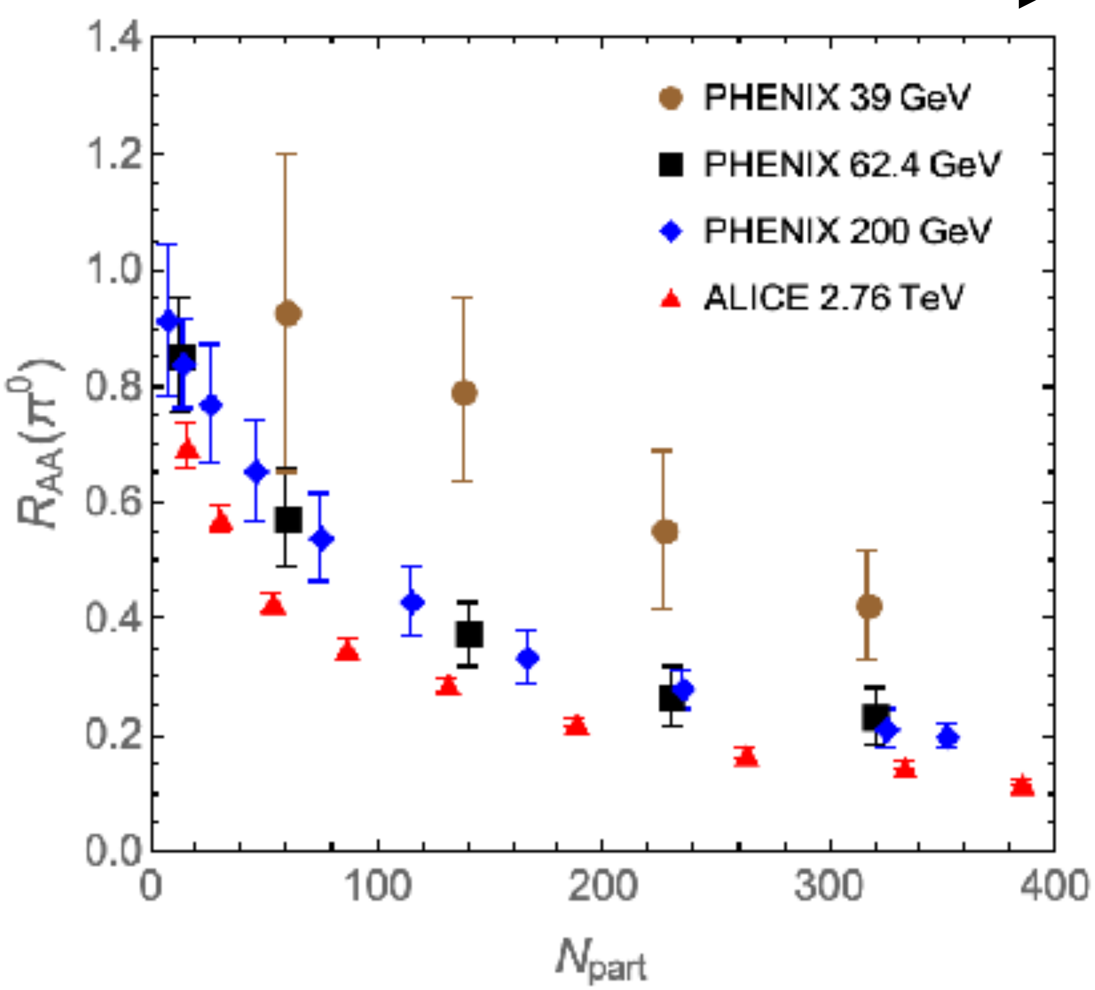


$$\frac{dE}{dx} = -C_2 \alpha_s \hat{q} L$$

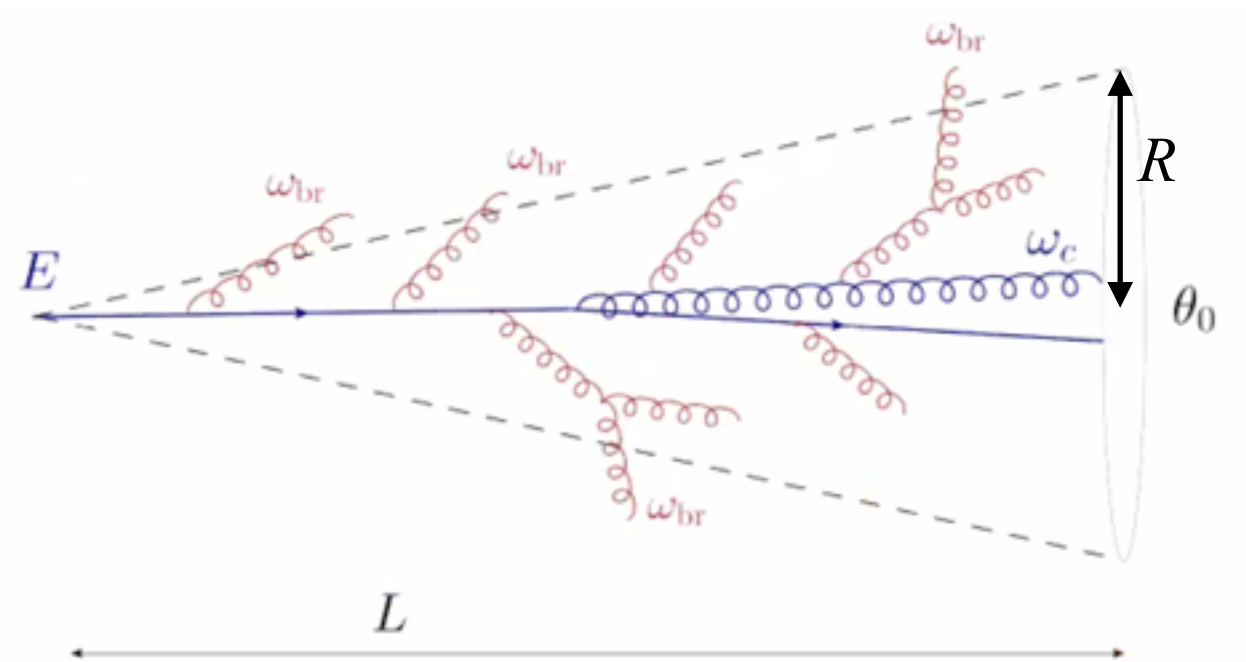
Energy loss of leading parton by gluon radiation

Measures gluon density in the QGP

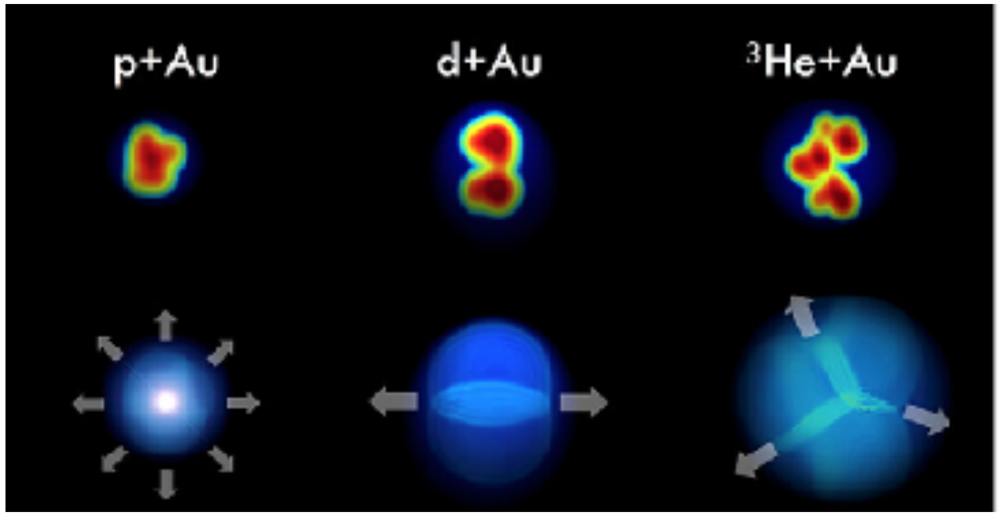
More central



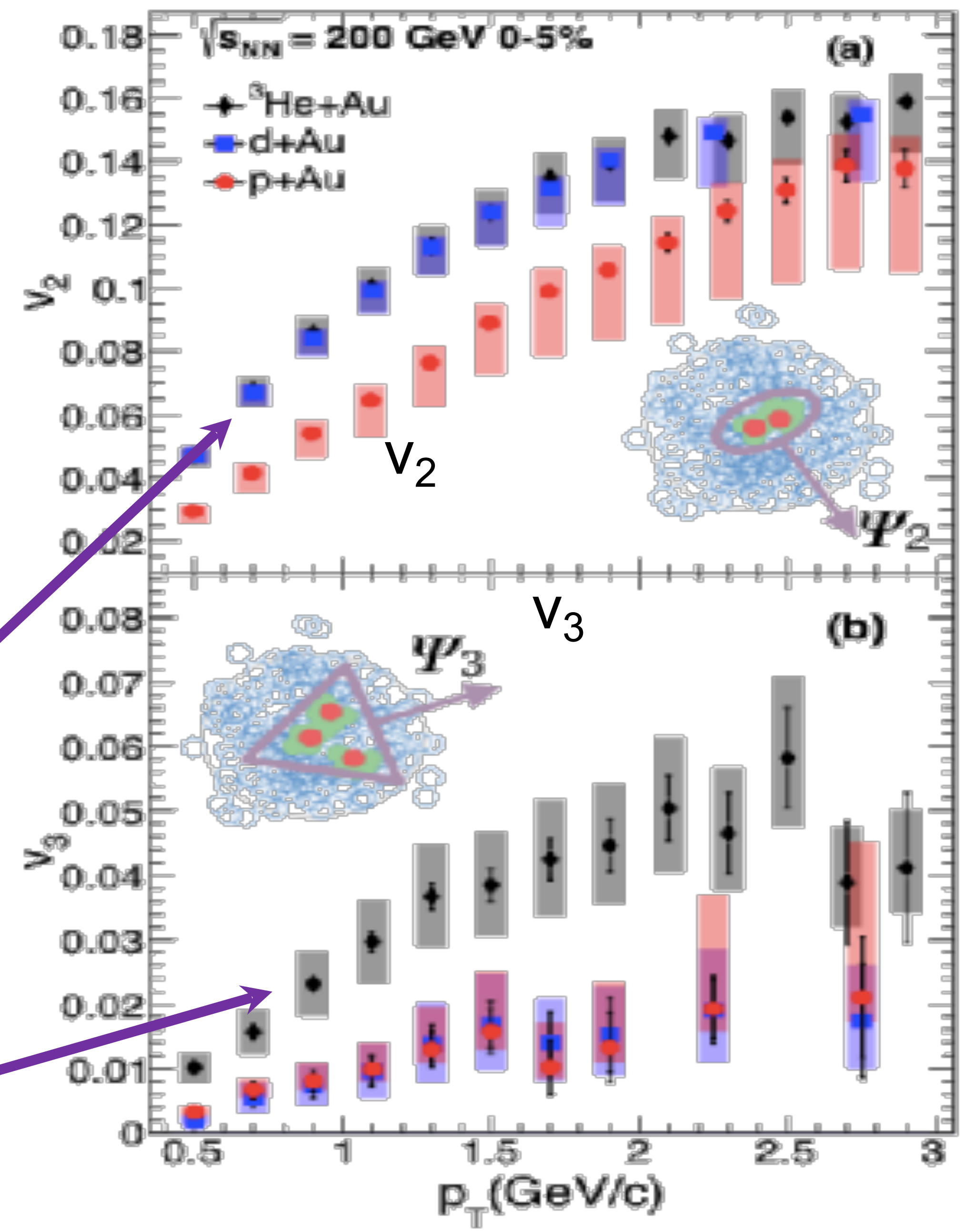
Jet energy loss measures energy radiated outside the jet cone with opening angle R



Geometry rules the day



The QGP droplets created in collisions of p+Au, d+Au, ³He+Au have characteristically different shapes resulting in different emission patterns.

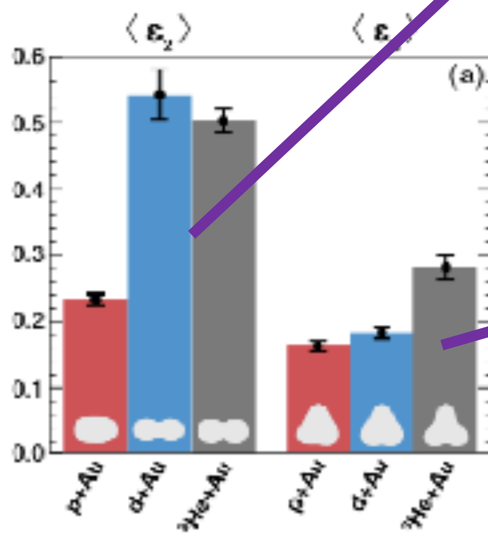


³He+Au
d+Au
p+Au

³He+Au

p+Au
d+Au

The ordering of flows follows the ordering of shapes (ε_2, ε_3)

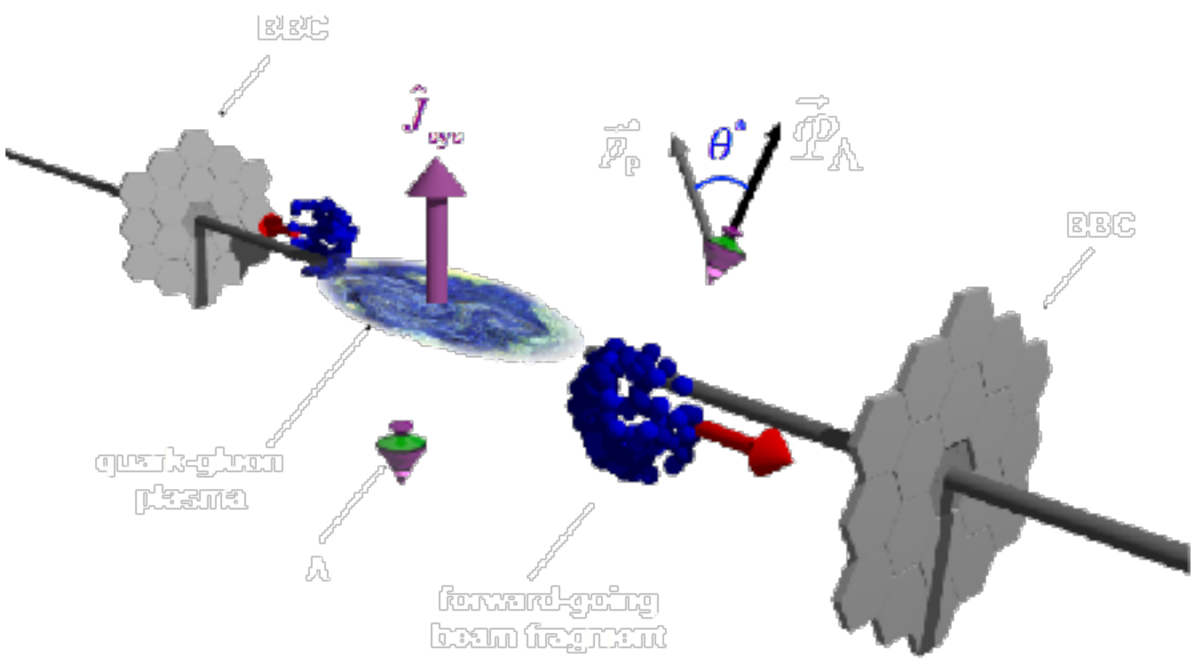


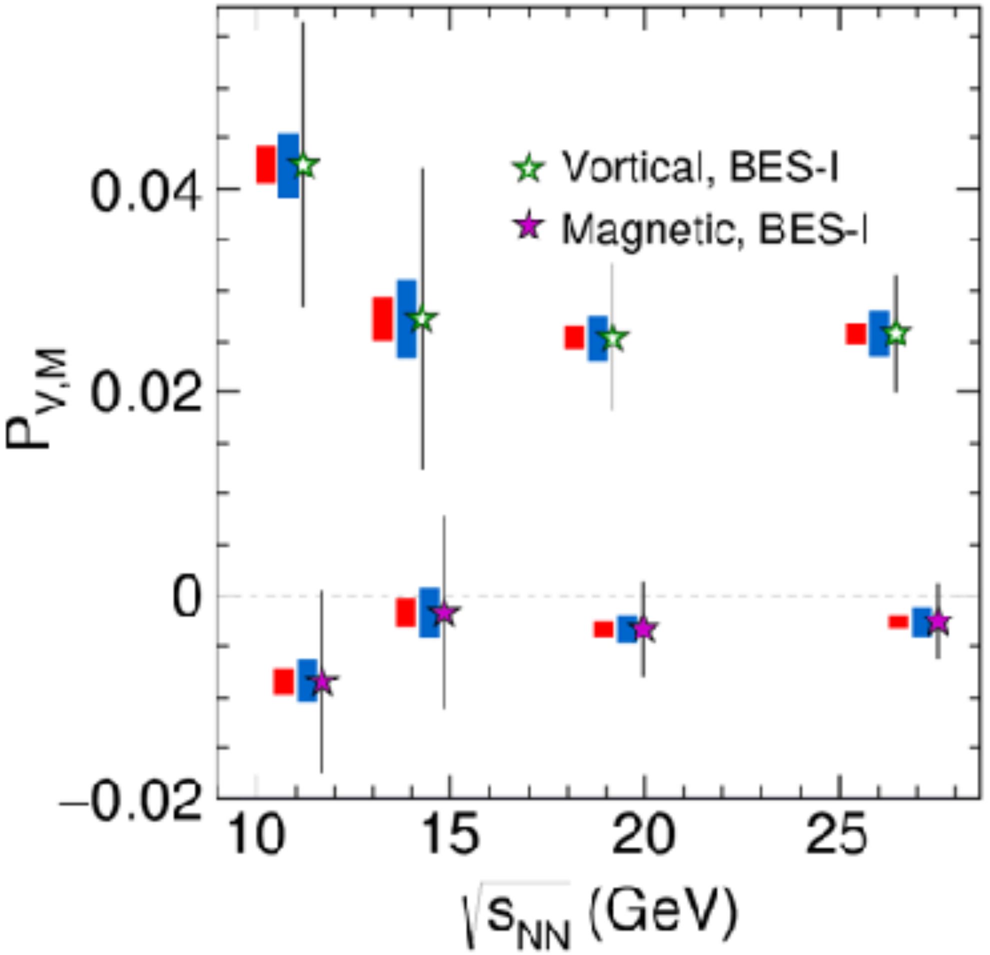
v_2(d,³He+Au) > v_2(p+Au)

v_3(³He+Au) > v_3(p,d+Au)

Surprises: Global Λ polarization

New tool to study QGP and relativistic quantum fluid vorticity





$$P_V = \frac{P_\Lambda + P_{\bar{\Lambda}}}{2}$$

$$P_M = \frac{P_\Lambda - P_{\bar{\Lambda}}}{2}$$

Global angular momentum transfer to hyperon polarization

Late time magnetic field would generate difference between hyperons and anti-hyperons

Precision result at 200 GeV:

$$P_H(\Lambda)\ [\%] = 0.277 \pm 0.040(\text{stat}) \pm^{0.039}_{0.049}\ (\text{sys})$$
$$P_H(\bar{\Lambda})\ [\%] = 0.240 \pm 0.045(\text{stat}) \pm^{0.061}_{0.045}\ (\text{sys})$$

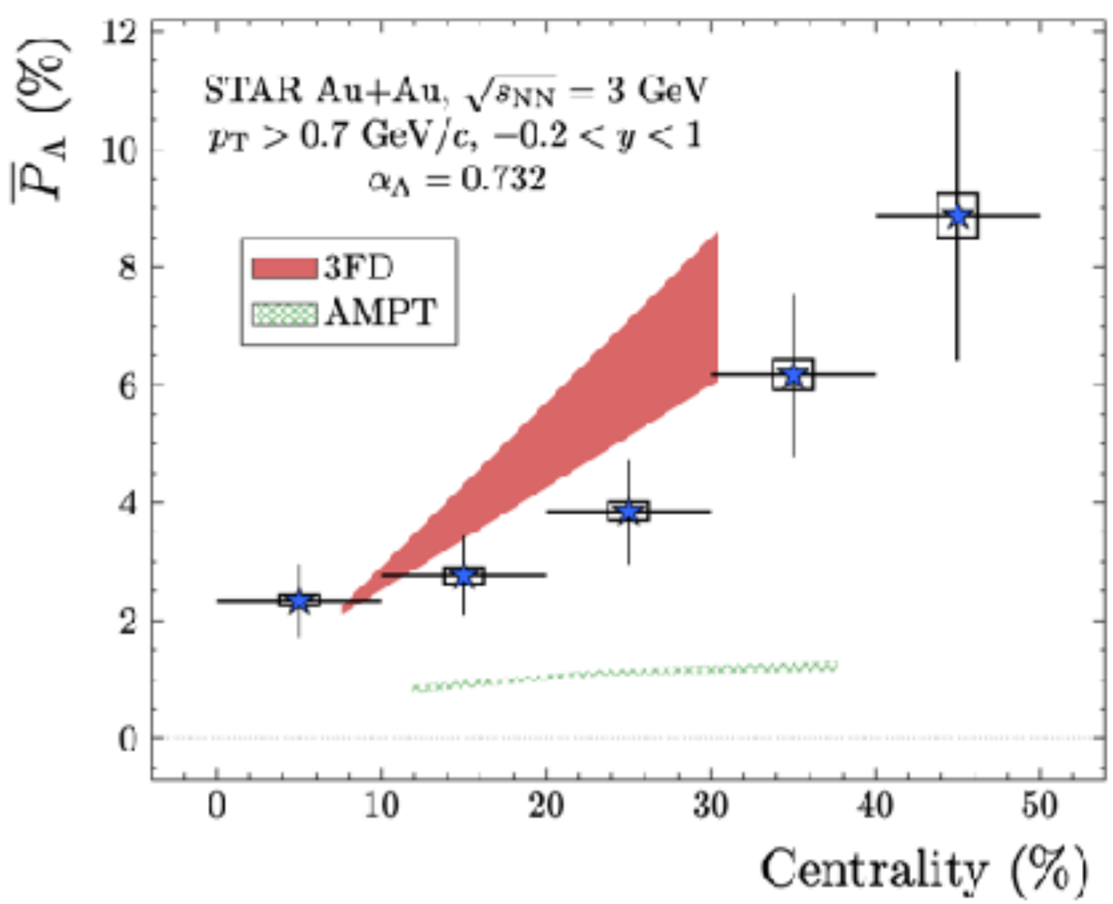
Implies: $|B| = \frac{T_s}{2|\mu_\Lambda|}|\Delta\mathcal{P}| < 8.9 \times 10^{11}\ \text{T}$

Vorticity structure

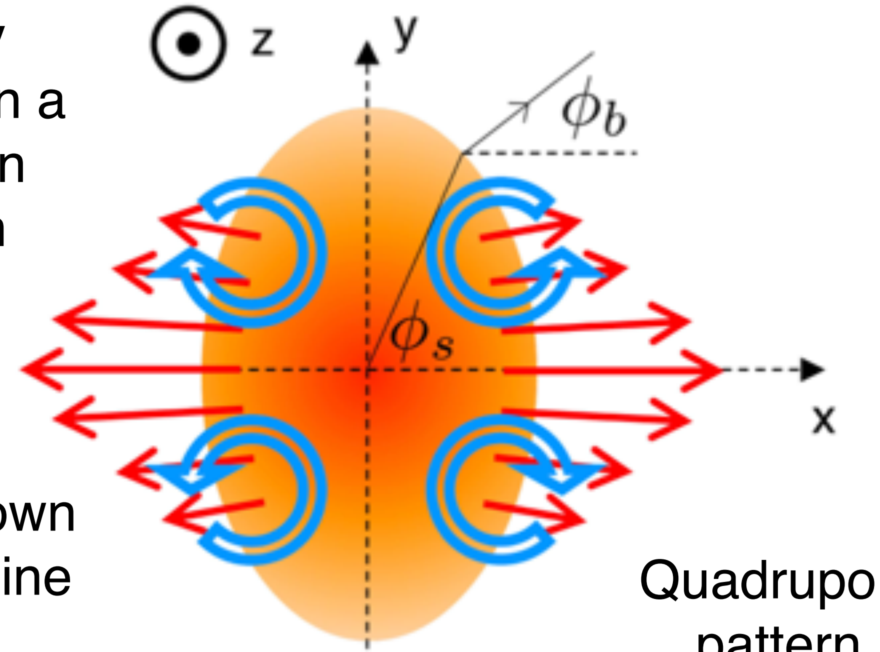
Angular momentum of colliding nuclei:

$L \sim p_{beam} b$

→ effect increases with off-centrality

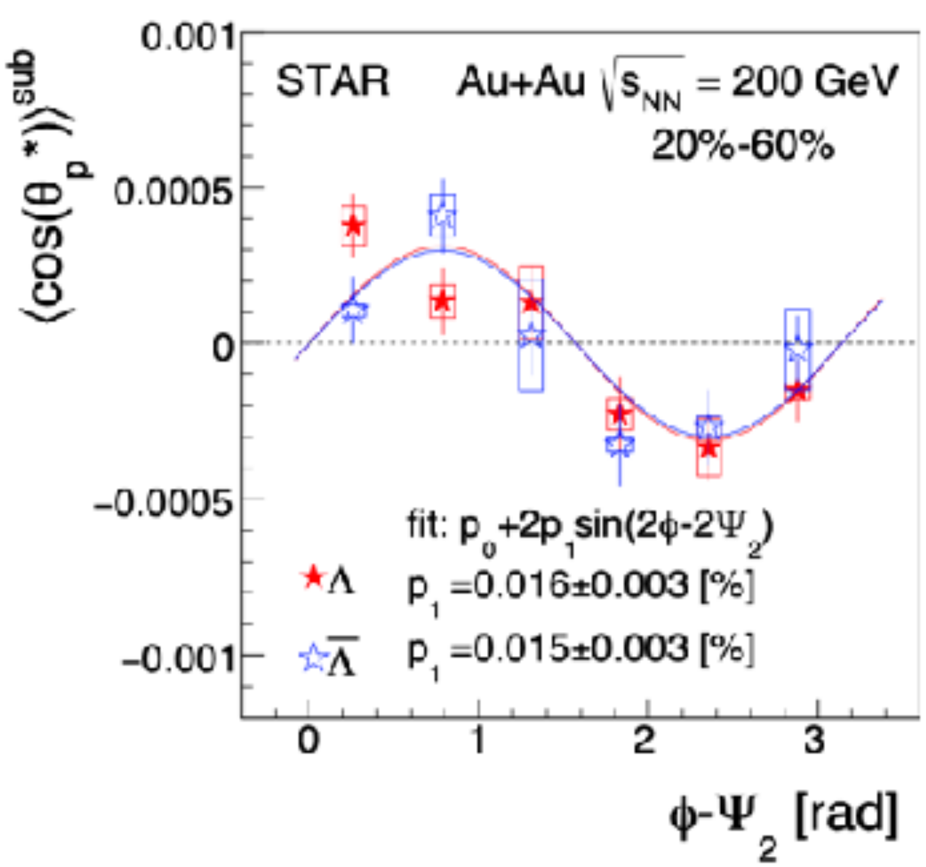


Vorticity structure in a heavy ion collision

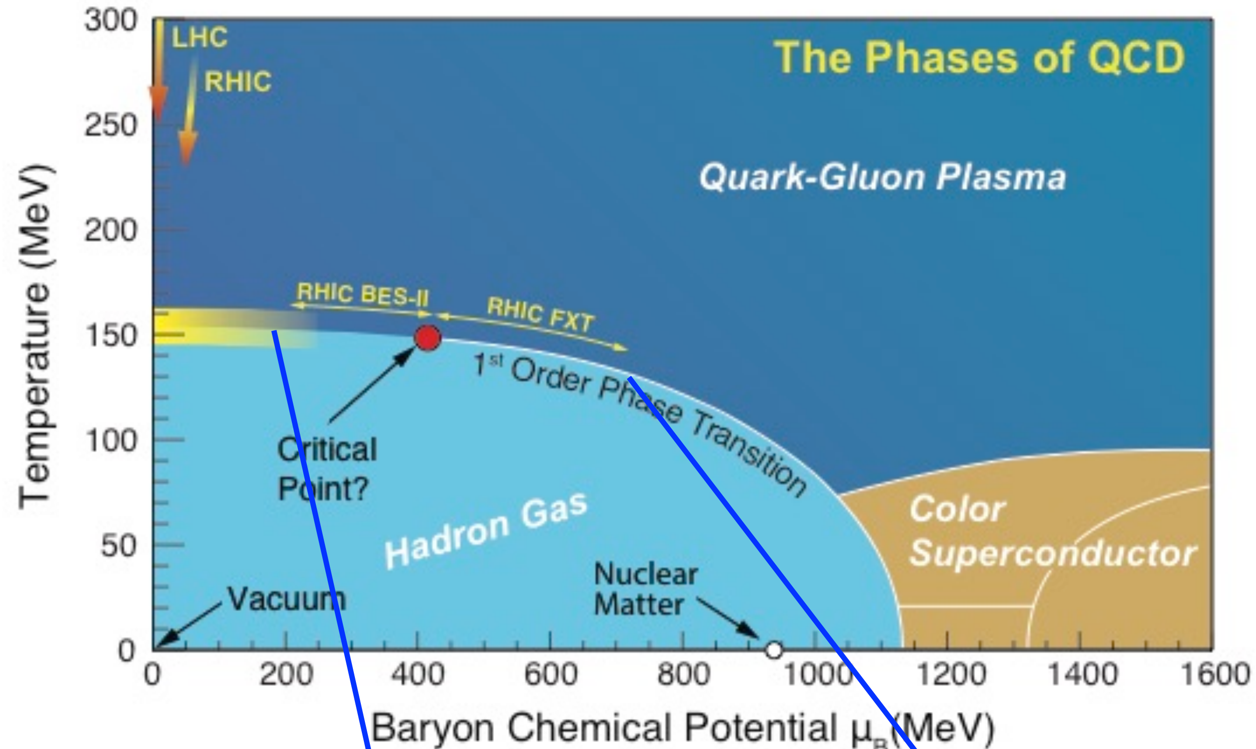


Looking down the beam line

Quadrupole pattern

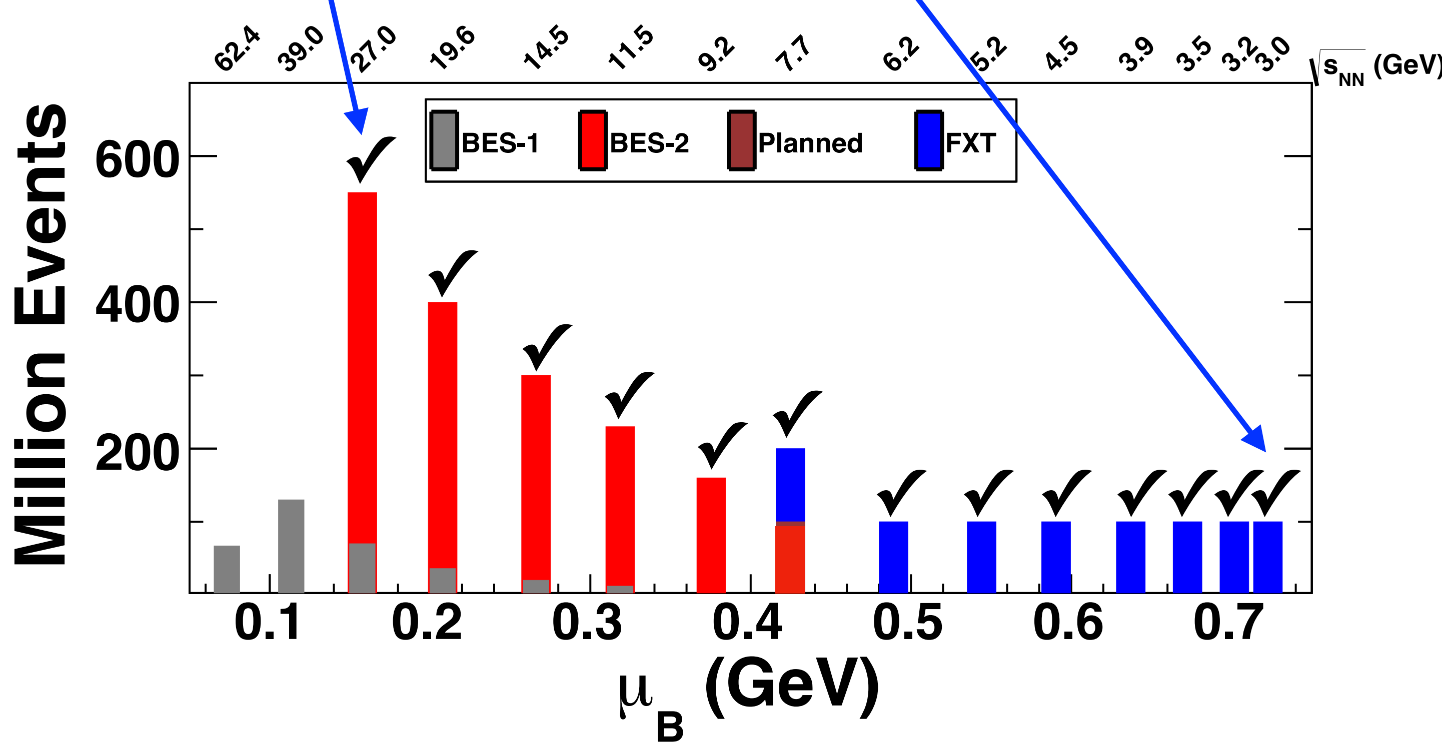


RHIC: Precision Beam Energy Scan

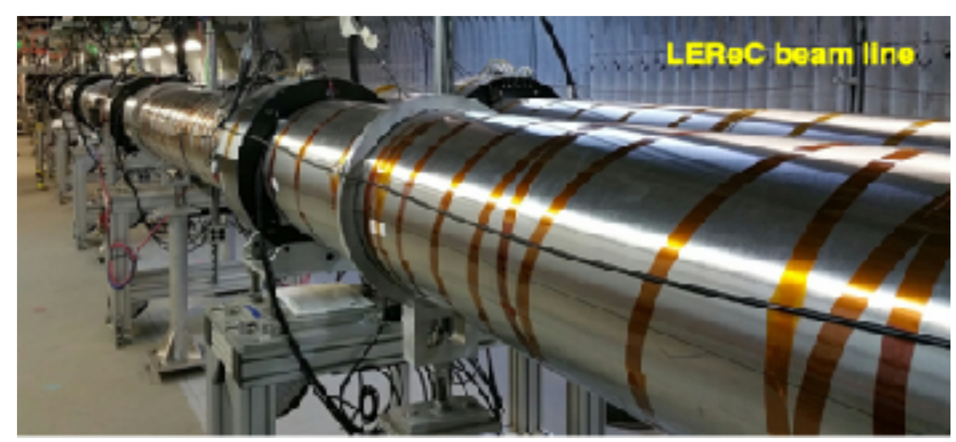


Beam Energy Scan Goals

- Where is the phase boundary of ordinary nuclear matter, i.e. matter composed of baryons and mesons?
- Is there a critical point in the QCD phase diagram and, if so, where is it located?
  - 3-year run program: 13 energies (14 runs)
  - 7 energies new (fixed target)
  - >10-fold statistics for all energies
  - **13.7 beam energy scan runs complete!**

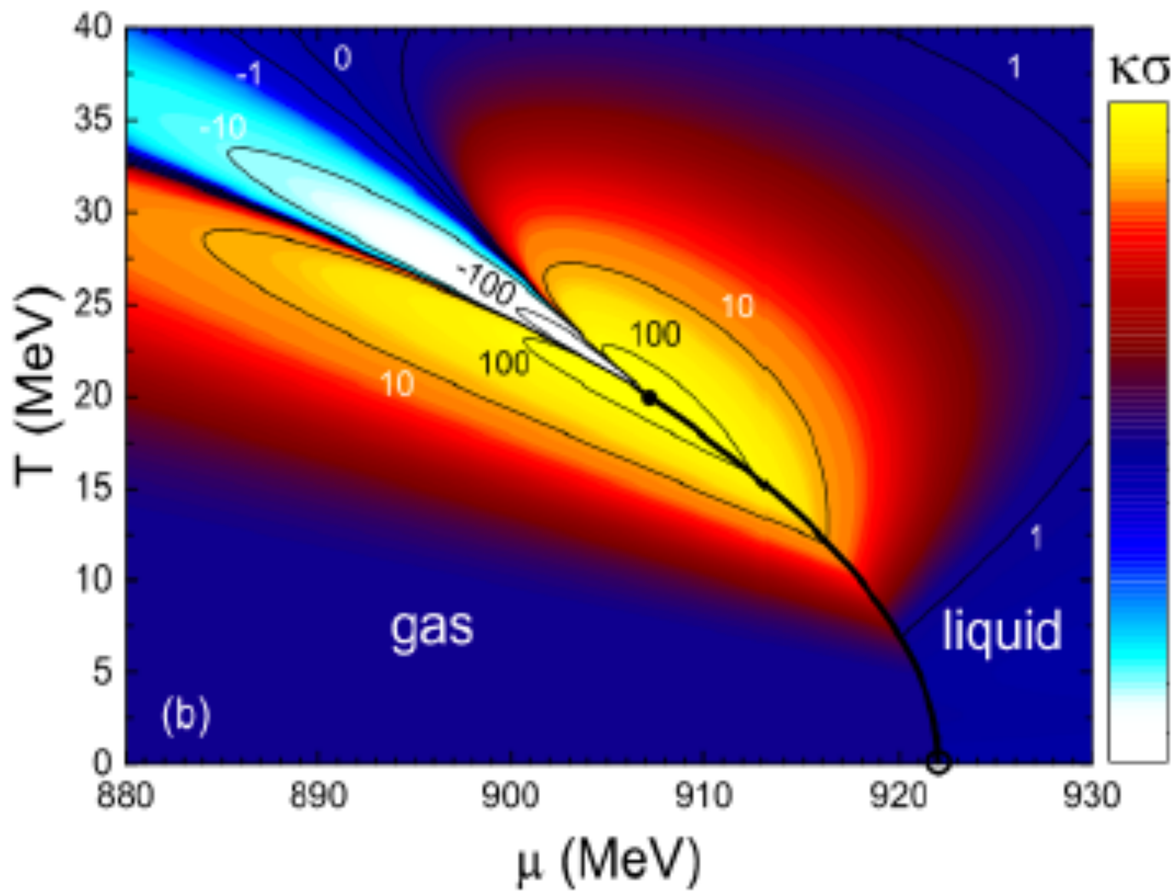


Low Energy RHIC electron Cooling
First-ever electron cooling with bunched beams
Test case for electron cooling at EIC

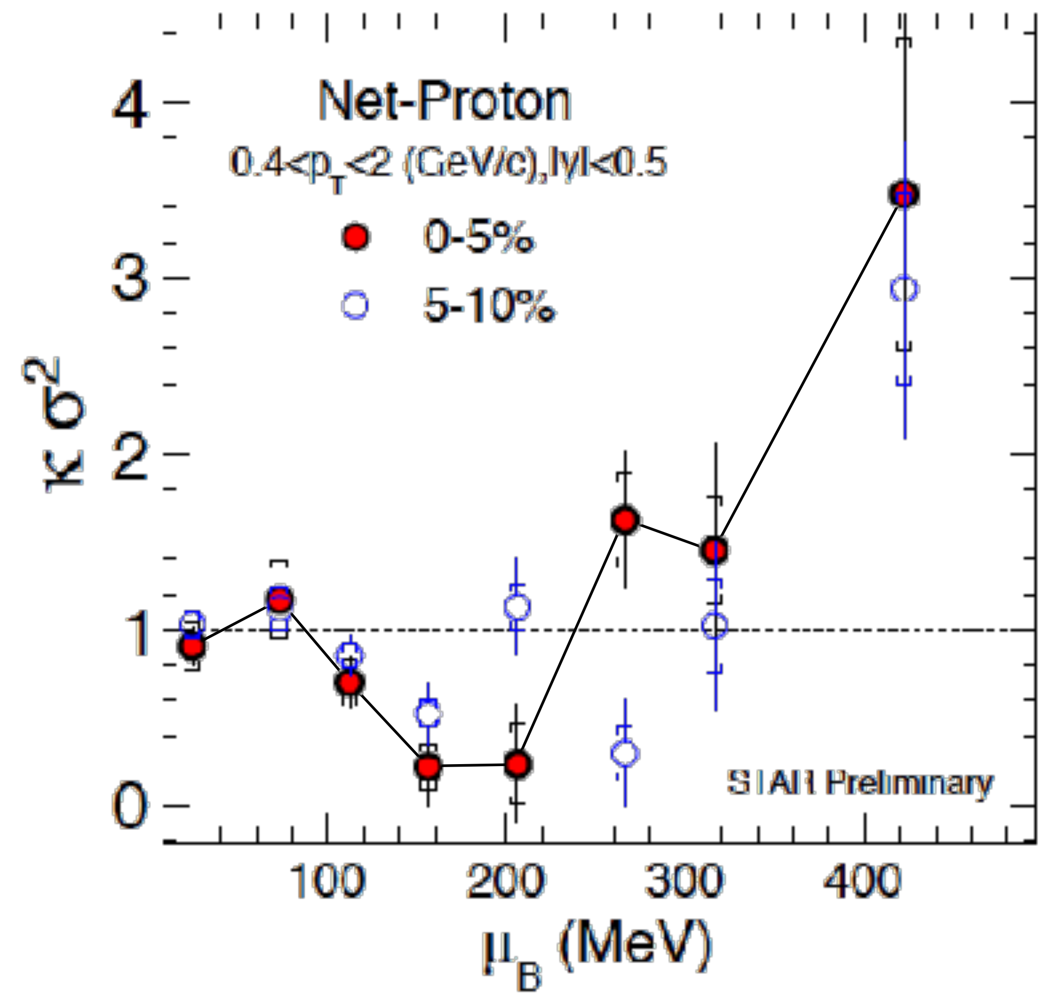


Critical behavior signals

The moments of the distributions of baryon number are related to critical susceptibilities and sensitive to critical fluctuations



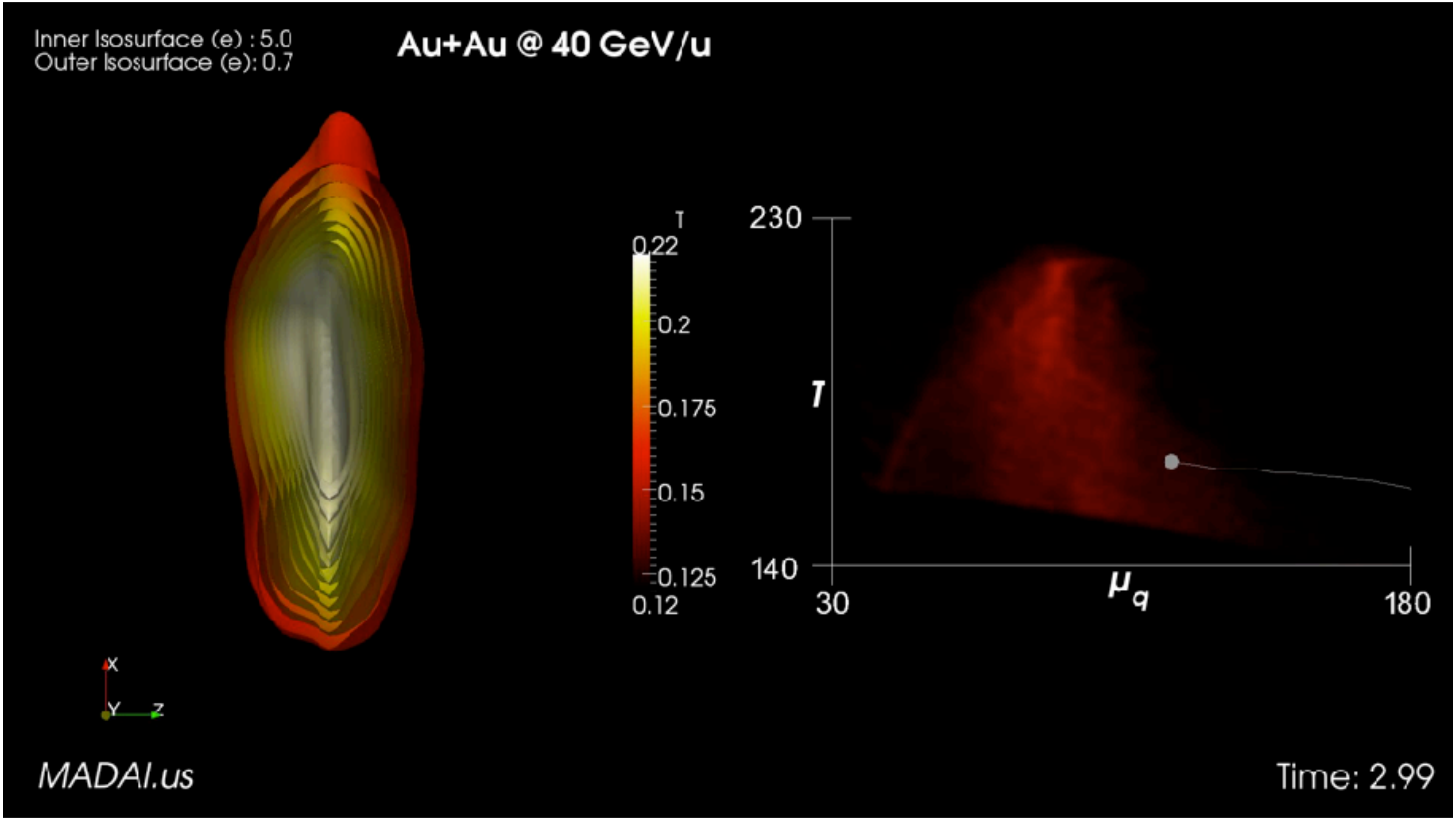
Higher moments (kurtosis) change sign at the critical point



Non-monotonic trend observed in BES-I with limited statistical precision

Hunting for the Critical Point

Visualizing RFD "trajectory" in *T*-*μ* space



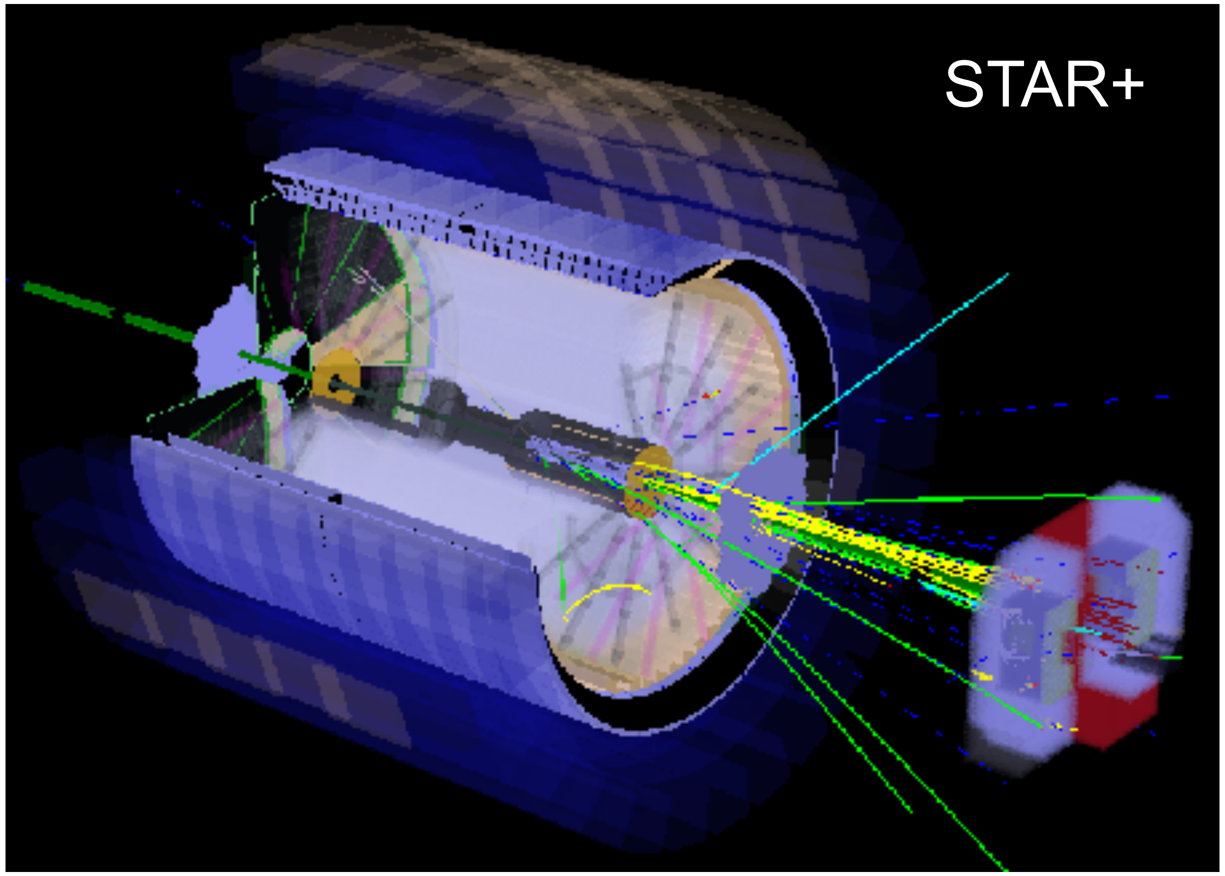
More to come: STAR+

- STAR collaboration has installed forward upgrades for RHIC runs beyond BES-II. Upgrade was ready for 2022 RHIC (pol. pp) run
- Extends rapidity coverage in the forward direction
- Very cost-effective upgrades with major non-DOE contributions

Refurbished EMCal, new Hcal, STAR Pre-shower, FMS, and sTGC based tracking system, covering $2.5<\eta<4$, forward Si tracking.

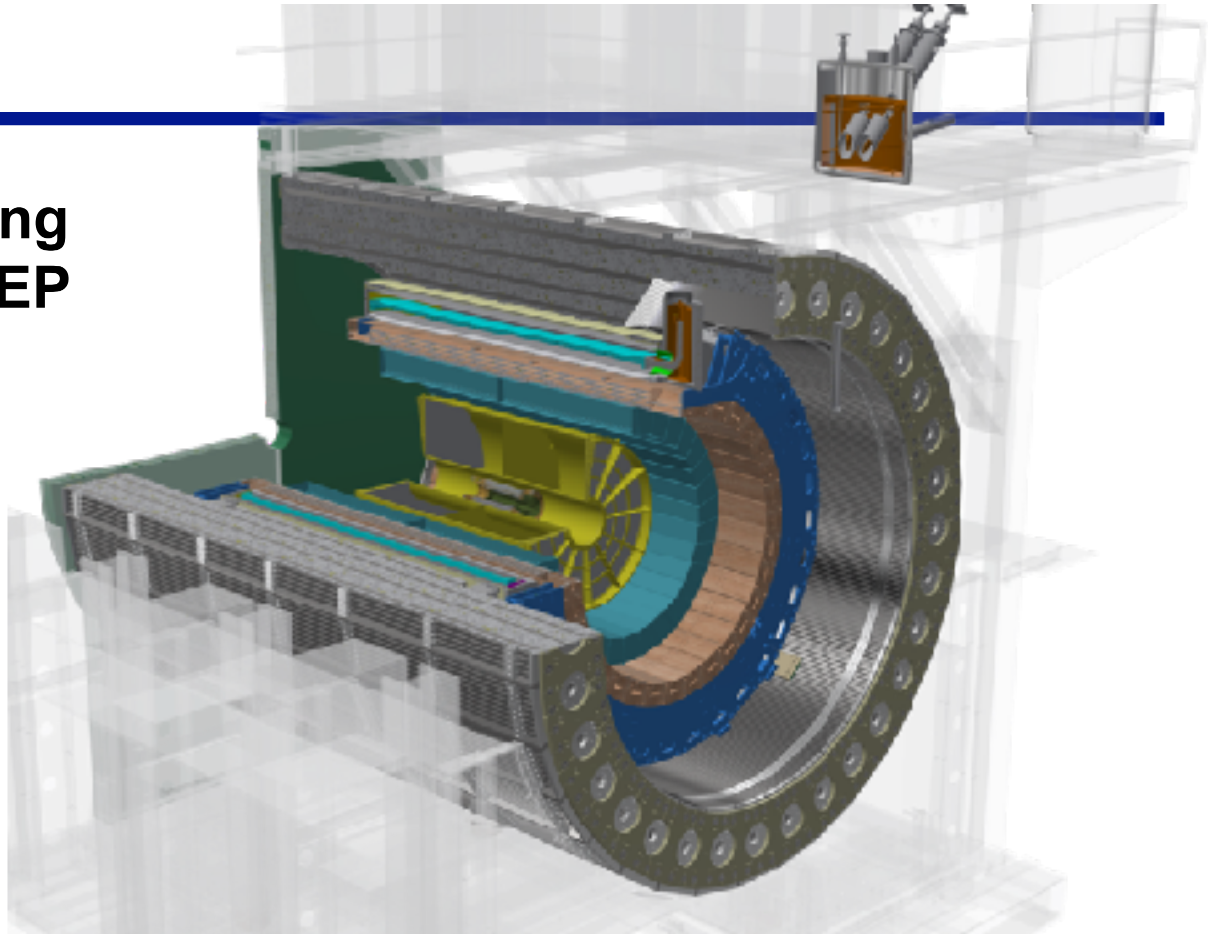
Commissioned in polarized 500 GeV proton run in 2022

STAR+ will take data with heavy ions starting next year

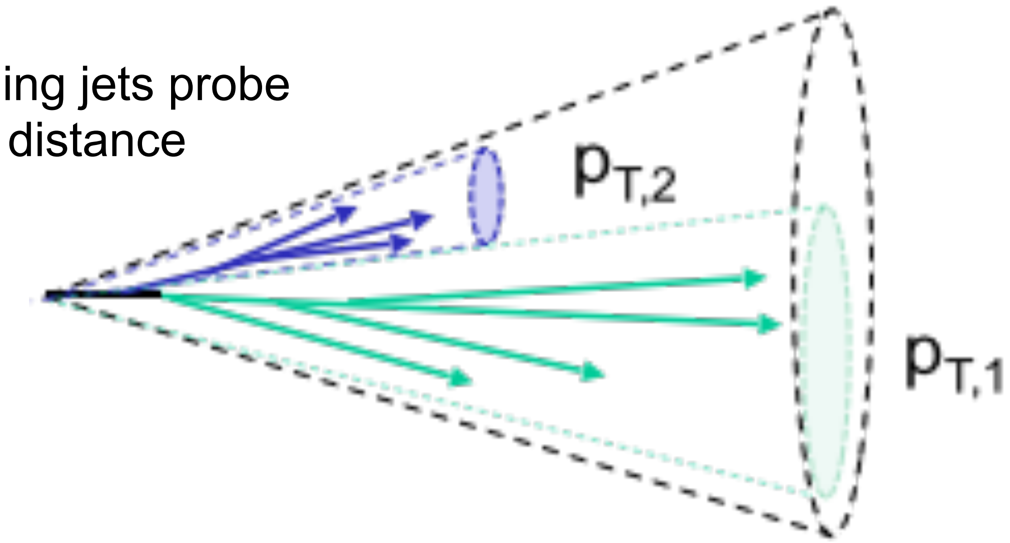


sPHENIX

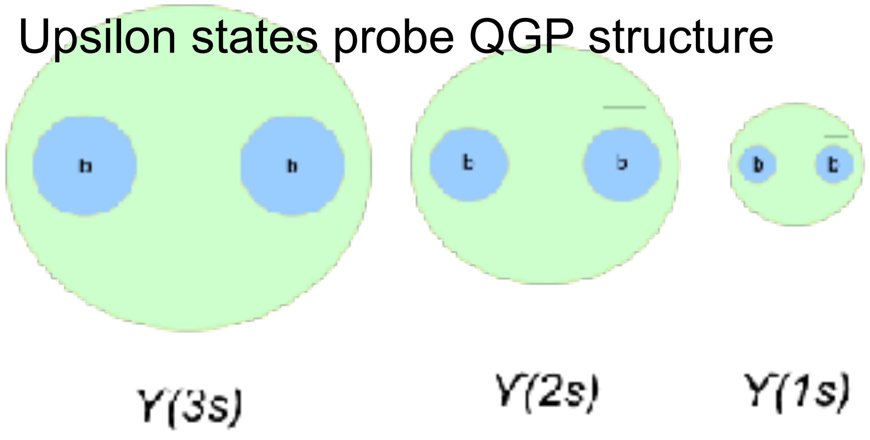
- **State-of-the-art collider detector incorporating technology developed for LHC by NP and HEP**
- **Assembly complete end of 2022**
- **Data taking to start in 2023**



Expanding jets probe various distance scales



Upsilon states probe QGP structure



- **High energy jets probe the structure of the QGP on different length scales**
- **Heavy quark atoms (Upsilon) also probe the QGP structure at different scales**
- **Heavy flavor hadrons and jets probe the transport properties of the QGP**

sPHENIX will increase the data collection rate by a factor of 10 and utilize the enhanced RHIC luminosity

RHIC & PRL

- RHIC has already left a legacy in PRL:
  - STAR: 88 with 18,556 citations (all with J. Sandweiss)
  - PHENIX: 75 with 16,645 citations
  - PHOBOS: 15 with 2,641 citations
  - BRAHMS: 10 with 2,287 citations
- Most recently:

PHYSICAL REVIEW LETTERS **126,** 162301 (2021)

Global Polarization of Ξ and Ω Hyperons in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

PHYSICAL REVIEW LETTERS **127,** 092301 (2021)

Observation of $D_s^{\pm}/D^0$ Enhancement in Au + Au Collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV

- And he isn't done yet: 4 new arXiv preprints in 2022 !

An interesting paper and a cup of coffee…

What more does a physicist need?